STRATEGIC ROTATIONS: SHARED MENTAL ROTATION PROCESSES ACROSS FIGURES AND ROOM-SIZE ARRAYS

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ABSTRACT

Do response functions of holistic and piecemeal- consistent stimuli reflect mental rotation strategies? Do individual differences mirror the response patterns of strategy-consistent stimuli? Do people engage similar processes and strategies when remembering room-size arrays? Current work examined the relationship between mental rotation strategies (holistic and piecemeal) and strategy consistent stimuli (whole vs. cut) and individual differences (gender, spatial information preference, and mental representation). Questionnaire responses provided information on spatial information preference (map, verbal directions) and mental representation style (survey, landmark). Experiments 1 and 2 used standard 3-dimensional and 2-dimensional abstract figures, respectively. Along with whole figures, "cut" versions were introduced to be consistent with strategies; whole stimuli eliciting holistic and cut eliciting piecemeal processing. These two experiments showed the classic MR finding-- increases in angular error and reaction time with increased angular disparity. Stimulus consistency showed *strategy difference pattern* as well as individual difference measures. Piecemeal versus holistic strategy use has been shown to become more apparent as the task at hand gets more complex (greater angular disparity), suggesting their role in mental rotation strategies. Experiments 3 and 4 investigated the evidence of shared cognitive processes with room-size arrays from memory based in different geometrical structures (circular, rectangular) and information source (direct experience, map). Participants in these experiments learned object arrays either as a whole or in separate halves and then decided whether three-object-configurations represent the same, yet rotated, or mirror-reflections of the original array. These two experiments showed that individual measures differentially interacted with

room/map geometry and learning source. Survey-representation and map preference, which were suggested to reflect holistic processing, led to better performance after learning from direct experience. Moreover, differences reflecting strategy were evident with geometry of the array. Learning whole array was better represented with circular maps, and learning array one half at a time fit better with rectangular maps. Taken together, the present four experiments found all of these variables (complexity, figure consistency, gender, preference, and representation style) showing *strategy difference pattern* that has been hypothesized to reflect holistic and piecemeal strategies. This is an interesting and new finding for the literature.

TABLE OF CONTENTS

LIST OF FIGURES

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Dave and Judy move to a new apartment. The delivery guy brings the sectional they chose a day earlier and places the parts across the room. Both Dave and Judy try to figure out how to fit the sectional in their living room. Although they come up with the same location, Dave made his decision more quickly. Talking about how they concluded where it should go, they realize differences. While Dave rotated the sectional as a whole, Judy rotated the pieces one by one, which may have been a reason why she contemplated the solution a little longer. Why did they adopt different strategies? What processes underlie their strategies? Would these differences emerge in other situations? Think about the same couple going out to explore their new neighborhood. Would their strategy difference in rotating the sectional transfer to the way they figure out the layout of the neighborhood? What if they used a map to navigate?

The current research addresses issues underlying these questions. The ability to use spatial information is essential in everyday life, e.g., moving without bumping into the furniture, knowing the direction between home and work. Yet, despite its importance, many questions remain about individual differences in spatial processing. Why is it that people process the same information differently? The current research, therefore, proposes to examine cognitive strategies underlying spatial processing, in particular the use of mental rotation, across scales, from block figures on a page to objects within a room. The review of the literature will start by explaining mental rotation tasks and how cognitive strategies affect the performance on these tasks. It will continue by examining mental rotation in navigational tasks (e.g., direct experience in a room), investigating

whether similar cognitive strategy differences exist when creating mental models of environments.

Small-scale spatial information processing involves mentally rotating manipulable (in size) objects and being able to see in the mind's eye what they would look like from different viewing perspectives. To compare whether the two objects are the same, one mentally moves the figure around to decide whether they match one another. Large-scale spatial information processing involves mentally navigating within an environment (Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006; Hegarty & Waller, 2004), but even here the scale of the environments can vary dramatically from keeping track of an object after changing position in a room to understanding the layout of a college campus. To sum up, mental manipulation takes place in both small- and large-scale environments, but to what extent are the underlying cognitive processes the same?

Mental Rotation Task

In a classic *Mental Rotation* (MR) experiment (Shepard and Metzler, 1971), participants decide whether two 3-D cube figures are the same or mirror-image of one another (see Figure 1). To make this decision participants mentally rotate one figure to align with the other. Thus, a typical mental rotation task consists of several steps (Cooper & Shepard, 1973; Just & Carpenter, 1976). A person first encodes both stimuli then mentally rotates one until it reaches alignment with the other. Once aligned, the person compares the figures, deciding whether they are the same or different, and then responds.

The major finding from classic mental rotation studies shows a linear relationship between the angular disparity between the figures and response time (Shepard & Metzler,

1971) and accuracy (Butler et al., 2006). This finding has been consistently shown with paper-pencil mental rotation tests (MRT) (Vandenberg & Kuse, 1978), computerized versions (Bryden, George, & Inch, 1990), and in eye fixation results (Freedman & Rovegno, 1981; Just & Carpenter, 1976). The regression line showing the relationship between the degree of rotation and response was found to account for different steps of MR. The slope reflects mental rotation rate and the intercept includes encoding, comparison, and response processes (Kail, Carter, & Pellegrino, 1979; Lohman, 1986).

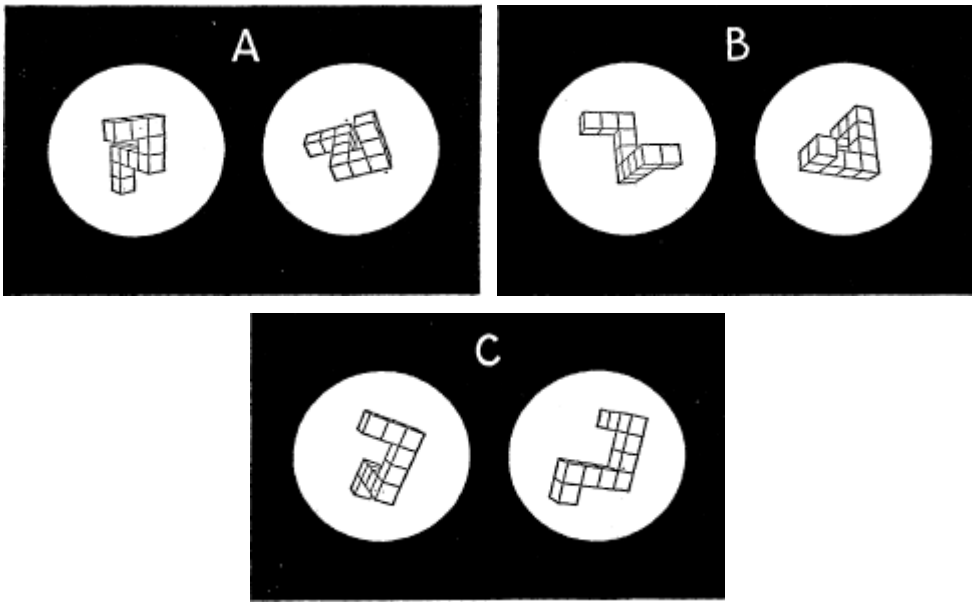


Figure 2. The pairs on the top (A and B) depict "same" image pairs and the pair at the bottom (C) show a pair of mirror-images.

The MR literature also frequently reports performance differences across genders. Gender differences in cognitive tasks have long been a topic of inquiry. The most consistent findings have been on spatial and verbal abilities, with the former favoring men and latter favoring women (Collins & Kimura, 1997; Kimura, 1999). Gender differences in spatial ability, specifically MR, continue to capture research attention. Common differences show that men mentally rotate images faster than women (Kail, et

al., 1979; Linn & Petersen, 1985; Maccoby & Jacklin, 1974; Masters & Sanders, 1993; Resnick, 1993; Richardson, 1994; Voyer, Voyer, & Bryden, 1995) although accuracy is often comparable (Kail et al., 1979; Voyer & Bryden, 1990).

Although the perception of a male advantage in mental rotation is well established, in reality the finding may be more ethereal. Some studies have found no gender differences (e.g., Butler et al., 2006; Voyer & Bryden, 1990) especially when instructions emphasized general rather than spatial thinking (Scali, Brownlow, & Hicks, 2000), that women did better than men (Moe, 2009) or when the stimuli were haptically or visually experienced replicas of the 3-D figures rather than drawings (Robert & Chevrier, 2003). Other studies have shown a female advantage (e.g., Uecker & Obrzut, 1993). These reports of no difference or a female advantage suggest differences in the underlying cognitive mechanisms. Do men and women use different cognitive strategies? Can slope and intercept provide more insight as to where the difference stems from? Difference between men and women appear in measures of mental rotation processing, such as steeper slopes (see Figure 2). Women also show a positively skewed response distribution compared to men's normal distribution (Kail et al., 1979; Lohman, 1986). Greater variability among women and difference in slopes between two groups suggest a possible pattern that is indicative of strategy distinction.

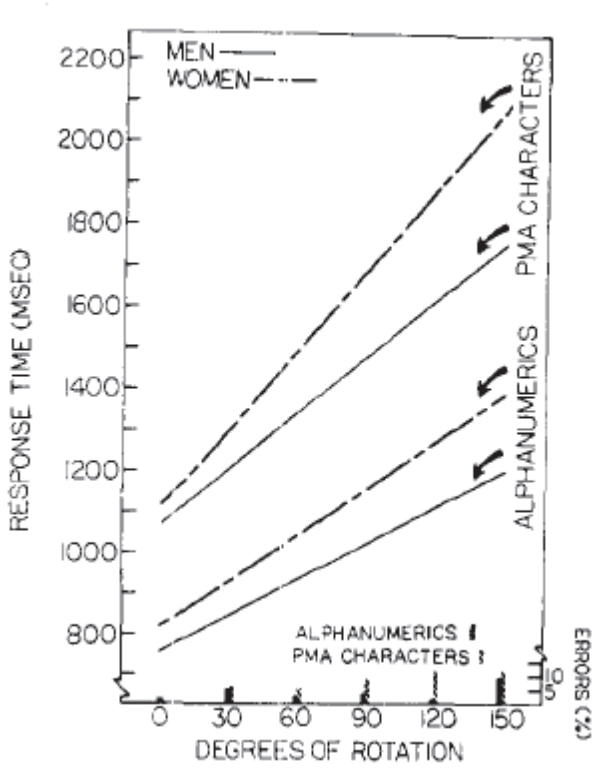


Figure 2 shows average response time (left axis) and errors (right axis) as a function of angular disparity (from Kail et al., 1979).

Strategies in MR

Two main strategies have been proposed for mental rotation: holistic and piecemeal. In holistic the figure is rotated as a whole and in piecemeal it is broken down into parts which are then rotated separately (Robertson & Palmer, 1983; Yuille & Steiger, 1982). Some researchers have suggested another way to conceptualize this difference by claiming that holistic involves more spatial processing and piecemeal relies more on reasoning and feature-by-feature non-spatial comparison (Geiser, Lehmann, & Eid, 2006). Men are proposed to use a more holistic strategy, which explains the male response time advantage, whereas women may more likely use a piecemeal strategy, which would take longer (Robertson & Palmer, 1983; Yuille & Steiger, 1982). Hemispheric laterality observed in MR provides further evidence for strategy use. While

mental rotation of simple figures was found to rely on the right-hemisphere, especially for a holistic strategy, left-hemisphere was more involved with piecemeal, analog strategies (Corballis, 1997).

To test the use of strategies, stimuli have been modified in complexity (Bryden et al., 1990; Naylor, Taylor, & Cross, unpublished data; Yuille & Steiger, 1982) and dimensionality (Bauer & Jolicoeur, 1996; Peters et al., 1995). Naylor and colleagues (unpublished data) created stimuli designed to test holistic versus piecemeal strategy differences. Participants viewed 3-D cube figures that were either continuous or cut in half to facilitate a piecemeal strategy. They hypothesized that if females already use a piecemeal strategy, their MR performance would not differ between cut and continuous figures. Females would use a piecemeal strategy with whole and cut figures. With males, on the other hand, it was hypothesized that if they use a holistic strategy in typical MR studies (i.e., whole figures), the cut figures would force a piecemeal strategy, thus showing different performance between the figure types. Although, no overall gender differences were found in reaction time or accuracy, results suggested strategy differences showing an interaction between gender and object type. As predicted, females responded similarly to cut and whole images, however males differed for the two figure types. Females consistently approached to stimuli whereas males sought for efficient strategies as stimuli changed (Naylor et al., unpublished data).

Other approaches have also been taken to vary stimulus complexity so as to test whether increased complexity might force a more piecemeal strategy (Corballis, 1997). In the second experiment of Naylor and colleagues (unpublished data), the figures included shading to increase depth perception. When dimensionality is more easily

observed, stimuli are more likely interpreted as 3-D, and consequently as more complex. Additionally, experiments altered the number of blocks (Bryden et al., 1990), where top or bottom halves of figures stayed the same (Yuille & Steiger, 1982), or varied right-/left-turns (Bryden et al., 1990; Yuille & Steiger, 1982) within the stimuli. While some studies find a clear complexity effect with steeper slopes (e.g., Yuille & Steiger, 1982), others do not (e.g., Bryden et al., 1990). Researchers also compared responses to 2-D and 3-D figures. Although 3-D slope was reliably steeper than that of 2-D, women mentally rotated 2-D figures more rapidly while males favored 3-D (Bauer & Jolicoeur, 1996). This is also consistent with males' greater accuracy on 3-D figures but not on 2-D ones (Peters et al., 1995).

Does the MR task successfully measure mental rotation?

Strategy difference might also reflect the nature of the MR task. Standard MR studies include mirror-image pairs to encourage mental rotation. However, mirror-images have been referred to as "impossible problems" because of non-congruence between the images even after successful rotation (Kerkman, Wise, & Harwood, 2000). Possible or "same" pairs were found to be rotated faster than impossible pairs. Moreover, women and men did not differ on "same" stimuli, but women had more problems with the "impossible" rotations (Geiser et al., 2006; Kerkman et al., 2000). The findings suggest that the MR test may measure more than mental rotation; the underlying mechanism for mirror-image stimuli appears different from those of the "same" stimuli (Geiser et al., 2006; Raabe, Hager, & Delius, 2006; Schultz, 1991).

MR performance differences may also reflect willingness to guess. With a time limit, women attack fewer MR problems (Peters, 2005) and have a tendency to confirm

their answers whereas men show more guessing (Voyer, Rodgers, & McCormick, 2004; Voyer & Saunders, 2004). When more or unlimited time was provided, women attempted more problems (Peters, 2005) and produced more guesses (Voyer et al. 2004; Voyer & Saunders, 2004). However, men also benefited from extra time and the performance difference between men and women remained.

The issues above might seem to put women at a disadvantage on MR tasks. MR ability, however, is interesting not because one group does better, but for what the differences suggest about cognitive strategies. Mental rotation is a spatial ability tested on a small-scale. How does mental rotation apply to the spatial task of room-size environments? Some studies suggest applicability of MR to larger scale navigation (Bell & Saucier, 2004; Boer, 1991). The similarities were drawn between mental rotation ability and mental navigation, which is necessary for perspective taking tasks (Allen, Kirasic, Dobson, Long, & Beck, 1996). Pazzaglia and colleagues (2000) devised a mental representation questionnaire where they could distinguish people's perspective preference for larger-scale environments. However, responses to this questionnaire, when applied to MR test, showed differences (Pazzaglia & De Beni, 2001). Thus, people need to mentally reorient their positions in the environment to understand how a layout would look like from other perspectives or viewpoints.

The role of mental rotation in perspective taking

Perspective taking is the capacity to decide on the appearance of an object or object array if viewing position changes. There are two alternatives on perspective taking in regards to mental rotation. While some propose that perspective taking is a mediator between small- and large-scale spatial information processing (Allen et al., 1996), others

claim that they are testing two different abilities (Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001). The latter view proposed a distinction between spatial visualization and spatial orientation. While spatial visualization accounted for mental manipulation of 2- and 3-dimensional figures, spatial orientation included mental navigation around a layout to imagine what it looked like from another vantage point using spatial memory (Linn & Petersen, 1985). People are required to do some kind of spatial transformations for both, but is it the same transformation? In mental rotation, object positions are moved while one's position in the environment does not. The opposite is true with perspective taking wherein the relations between the objects are stable and one's own position changes (Hegarty et al., 2006; Hegarty & Waller, 2004; Rieser, 1989). Researchers developed an Object Perspective Test to investigate whether perspective-taking and MR measure the same abilities and found a better fit for a two-factor model suggesting they are dissociable abilities (Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001; Kozhevnikov, Motes, Rasch, & Blajenkova, 2006).

Although perspective-taking and MR are proposed to measure distinct abilities, researchers cannot fully explain why some people might use similar strategies to solve both MR and perspective-taking problems (Hegarty et al., 2006; Hegarty & Waller, 2004). However, it is accepted that both of the tasks require encoding of spatial stimuli and forming mental representations (Kosslyn, 1994). Researchers also found positive correlation between MR and perspective-taking accuracy (Kozhevnikov et al., 2006). These results suggest that people might rely on similar mechanisms to solve both MR problems and perspective-taking tasks. Previous findings showed that people who rely on

different perspectives in creating mental representations through navigation performed differently on MR test (Pazzaglia & De Beni, 2001).

This idea was further supported by examining performance on navigation and MR tasks. Studies included perspective taking problems to investigate spatial processing of information on large-scale environments (Bell & Saucier, 2004; Boer, 1991; Kozhevnikov et al., 2006; Saucier et al., 2002) and compared findings with performance on standard Shepard and Metzler MR test (Kozhevnikov et al., 2006). While some studies reported little or no correlation between the two tasks (Kozhevnikov et al., 2006) others did show a correlation (Hegarty et al., 2006; Hegarty & Waller, 2004; Saucier et al., 2002). Another study examined orientation and disorientation in context of perspective taking. Participants pointed to previously learned city locations either when facing the same direction as when they learned (oriented) or a different way (disoriented with rotation) (Boer, 1991). To process how the layout would look from other directions, participants needed to mentally rotate the image. Confirming this hypothesis, results showed the increase in reaction time as the angular disparity of the perspective increases (Boer, 1991). This nicely mirrors the most basic linearity effect in MR (Shepard & Metzler, 1971). In addition, results of standard MR and pointing tasks in large-scale navigation displayed corresponding patterns (Bell & Saucier, 2004; Saucier et al., 2002) suggesting similar underlying processes between small- and large-scale testing.

Spatial representations in the mind

In everyday interactions with the spatial environment, whether small- or large-scale, there is generally too much information to process at once. A comprehensive representation is formulated through acquisition, encoding, storage, and if necessary,

recalling, and decoding (Downs & Stea, 1973). This series of processes results in a *cognitive map*. The term *cognitive map* was first used in Tolman's (1948) studies with rats. According to him, a cognitive map included locations and objects or events. Paths connect the locations within a space and objects are associated with the given space (Tolman, 1948). Since Tolman, the mental relationship between animals (including people) and their surrounding environment has been explained using different terms.

Spatial mental representations rely on reference frames (Levinson, 1996). In space every location can be placed on a coordinate system with an origin. The point of view and the reference terms vary with the origin of the coordinate system. The origin might be on an object, which is *intrinsic frame.* The intrinsic frame relates object-to-object locations. In *relative* or *egocentric* frame, the viewer is at the origin of the coordinate system and spatial information is represented in person-to-object manner. The *absolute* or *allocentric* frame also defines object-to-object relations using external, cardinal direction (e.g., south, north) coordinates (Easton & Sholl, 1995; Emmorey, Tversky, & Taylor, 2000; Franklin & Tversky, 1990; Sholl, 1987; Taylor & Tversky, 1996; Taylor & Tversky, 1992).

Spatial reference systems and perspectives vary according to the information source. Information can be gathered through direct experience such as walking in the environment or from secondary sources such as maps or verbal descriptions. While navigating in the environment, people relate their current position to the surrounding landmarks using a first-hand egocentric perspective. The point of view is within the environment using a *landmark* (Pazzaglia & De Beni, 2001) or *route* perspective. Artifacts such as maps, however, allow people to take a bird's eye view. The landmarks

can be more readily related to one another with an external point of view, using *survey* perspective (Taylor & Tversky, 1992). As in allocentric representations survey perspective utilizes cardinal directions.

Representations of the environment are encoded and kept in memory for later use, sometimes called spatial mental models (Franklin & Tversky, 1990). There are various theories on accessibility of spatial mental models. Spatial memory is proposed to depend upon two distinct systems; egocentric and allocentric representations (Easton & Sholl, 1995; Sholl, 1995). Easton and Sholl (1995) examined whether a person would retrieve an object's location relative to oneself through *egocentric* representation even when it is encoded *allocentrically*. Modeled after a study by Rieser (1989), participants were familiarized with an array of objects and then completed pointing tasks in which they imagined rotating and facing an object or imagined translating to a new position. Results showed that participants used allocentric representations after translation, but egocentric representations after rotation. Moreover, pointing latency linearly increased with the distance between the actual and imagined observation points (Easton & Sholl, 1995), showing consistency with MR and perspective-taking results.

Evidence for egocentric spatial mental model

Another theory on spatial mental models emphasizes the importance of egocentric representations (Wang & Spelke, 2000). This model was supported with a range of spatial updating results. In this section, spatial updating will be explained followed by an explanation of alignment effects, reorientation, and viewpoint-dependent versus viewpoint-independent spatial representations.

Spatial updating is a cognitive process wherein people continuously track environment locations, e.g., objects and landmarks, relative to their changing position in space (Amorim & Stucchi, 1997; Farrel & Robertson, 1998; Loomis, Lippa, Klatzsky, & Golledge, 2002; Wang & Spelke, 2000). Spatial updating appears to occur relatively automatically. When asked to rotate to face a new direction with their eyes closed, participants could change their heading as they imagined moving (Rieser, 1989) and imaginary rotation yielded results similar to actual movement (Easton & Sholl, 1995; Rieser, 1989). It is a dynamic yet limited capacity considering the amount of information that needs to be updated with multiple environments. Thus, people were found to apply a triage-like strategy with navigation, where they update egocentric spatial information favoring proximity (Wang, 1999; Wang & Brockmole, 2003a; Wang & Brockmole, 2003b).

In a typical experimental design, participants study and learn objects placed in a room (Easton & Sholl, 1995; Farrel & Robertson, 1998; Mou, McNamara, Valiquette, & Rump, 2004; Mou, Zhao, & McNamara, 2007; Rieser, 1989; Wang, 1999; Wang & Spelke, 2000). They then point to target objects with no vision after a slight move (rotation or translation) or disorientation (Wang & Spelke, 2000). The hypothesis was that if the spatial representation of the room and the objects were enduring global representations, disorientation should not disrupt updating (Holmes & Sholl, 2005; Mou et al., 2004). Alternatively, if the relative frame is used, relations between objects would be represented as a whole and disorientation would yield a fixed degree of error for all objects. However, if the spatial mental model involves transient egocentric representations, disorientation would interrupt the updating process yielding less accurate

pointing. In accordance with the egocentric updating model, updating was severely affected after disorientation, but intact after small rotations (Wang & Spelke, 2000).

In spatial updating, the egocentric reference frame aligns with the person's heading direction. However, if the heading at learning and the imagined heading differ people make more errors. This phenomenon has been called the *alignment effect* (Farrel & Robertson, 1998; Levine, Jankovic, & Palij, 1982). Farrel and Robertson (1998) designed a study based on the alignment effect wherein participants were asked to ignore their heading direction right after turning and point to objects as if they had not moved. Ignoring the movement took longer to process and produced more errors compared to pointing according to their actual heading. The result suggested automatic updating of the newly moved direction, aligned their actual heading with the egocentric frame. However, they must undo the process when asked to ignore their current heading, for which updating inhibited the new alignment.

Alignment process occurs by mentally rotating the imaginary heading and actual heading into congruence. In several studies, participants studied an array of objects where half of them learned the objects by moving around the array and the other half viewed the array moving (Mou & McNamara, 2002; Mou et al., 2004; Shelton & McNamara, 1997; 2004; Wraga, Creem, & Proffitt, 2000). Transforming an array of objects as opposed to egocentric transformations around an array was proposed to be different tasks (Amorim & Stucchi, 1997; Simons & Wang, 1998; Wang & Simons, 1999; Wraga et al., 2000). First of all, active movement was found to improve spatial performance (Wang & Simons, 1999). Self-rotation, even imaginary, yielded more accurate and faster performance than imaginary rotation of the object array (Wraga et al., 2000). With

imaginary self-movement, egocentric frame needs to be transformed whereas with imaginary object-rotations, object-to-object or allocentric frame is transformed.

Viewpoint-dependent spatial mental models

Spatial mental models of large-scale, navigable environments, such as directly experiencing an object array in a room were proposed to be viewpoint-dependent after studying from a single vantage point (Diwadkar & McNamara, 1997; Roskos-Ewoldsen. McNamara, Shelton, & Carr, 1998), two stationary viewpoints (Mou & McNamara, 2002; Shelton & McNamara, 1997; 2004), and multiple viewpoints (Diwadkar & McNamara, 1997; Mou et al., 2004). In Shelton and McNamara's study (1997) participants learned a room with seven objects from two viewing positions (0^0 and 90^0) and then completed directional judgments. The task required participants to imagine facing object A while standing at object B and point to object C. Both translation and rotation (Rieser, 1989) are necessary for this task. When the imagined heading was aligned with the actual viewing direction the task was easier (Klatzky, Loomis, Beall, Chance, & Golledge, 1998), supporting the alignment effect (Levine et al., 1982). In another study by Shelton and McNamara (2001), participants again learned layouts from two different viewpoints. They were then moved to another room and completed the directional judgment task from memory. The results together provided strong evidence for viewpoint-dependence (Shelton & McNamara, 1997) and even learning viewpoint dependence (Shelton & McNamara, 2001) with better representations of layouts when the imagined heading was parallel to the learning direction created from studying two viewpoints (Shelton & McNamara, 1997).

Viewpoint-independent mental representations and other spatial sources

Although the above studies suggest viewpoint-dependent spatial memory, other models (Easton & Sholl, 1995; Sholl, 1999) based on egocentric and allocentric representations propose viewpoint-independent representations, especially for object-to-object spatial relations.

To test whether mental representations are viewpoint-dependent or independent, studies compared learning spatial information from different sources. Shelton and McNamara (2004) investigated mental models created with spatial descriptions, where participants learned the layout from one view and described it to another person from multiple viewpoints. Pointing performance with the directional judgment task was better from novel imagined headings that were parallel to experimenters' suggesting that representations may not be learning viewpoint dependent, but relied on intrinsic reference frames, and intrinsic axes of the layout (Mou et al., 2007; Mou, Fan, McNamara, & Owen, 2008a; Mou, Xiao, & McNamara, 2008b; Mou & McNamara, 2002; Mou, Liu, & McNamara, 2009). In one of these studies (Mou & McNamara, 2002) participants learned an intrinsically set layout, not parallel to their viewpoint. They made judgments from memory. Performance was the best when imagined heading was parallel to the instructed direction, also supported with briefly viewed layouts (Mou et al., 2008b), eye movements (Mou et al., 2009) and scene recognition (Mou et al., 2008a), concluding spatial memory to be allocentric. However, the information source (primary or secondary) was assumed to account for different experiences and possibly different mental representations (Brunyé & Taylor, 2008; Shelton & McNamara, 2004).

In Thorndyke and Hayes-Roth's experiment (1982), some participants gathered spatial knowledge about a building by walking around while others studied a map. The use of different perspective by navigators and map-learners; route and survey, respectively, produced different results suggesting a viewpoint-dependent mental representation. When people navigated within the building, they used a route perspective and it allows for a specific viewpoint. However, when they familiarized themselves with the same building by studying the layout from a map, their viewpoint is more like a bird's eye view using a survey perspective. Performances of map and navigation learners varied as they used different viewpoints and perspectives. With moderate exposure, map-learners better judged relative locations and line-distances than navigators. However, with extensive exposure to the environment, performance between the two groups became more similar (Leiser & Zilbershatz, 1989; Thorndyke & Hayes-Roth, 1982), suggesting perspective-flexible mental representations (Brunyé & Taylor, 2008; Taylor & Tversky, 1996).

Sholl (e.g., Easton & Sholl, 1995; Holmes & Sholl, 2005; Sholl, 2001; Sholl & Nolin, 1997) proposes a two system model with inter-object relations of allocentric representation and self-to-object relations of egocentric representation. While allocentric representation uses a viewpoint- or orientation independent reference system, egocentric representation uses one's own orientation with body-front direction. The egocentric frame is especially used for judgments of relative direction and supports various phenomena, e.g., alignment effect, spatial updating, disorientation. However according to Burgess (2006) egocentric spatial system needs revision, because the existence of an egocentric representational system cannot explain the absence of allocentric system nor

exclude it. Therefore, both systems play into how spatial mental models would be formed.

External cues such as the structure of the learned environment or room geometry have been proposed to affect spatial mental models (Mou et al., 2007; Mou & McNamara, 2002; Shelton & McNamara, 1997). Structure of the environment was formed by framing the layout. McNamara and colleagues found framing an array of objects provided advantage for egocentric reference frame in forming spatial mental models (Mou & McNamara, 2002; Shelton & McNamara, 1997). Basing on this line of work, it is possible to predict cognitive strategy use and how it might affect standard MR performance. Holistic strategy provides mental rotation as a whole enabling a more global and allocentric representation of spatial information. With piecemeal strategy, however, each piece is rotated egocentrically to solve a mental rotation problem. Current research proposes further predictions including the framing effect. Framing the environment (rectangular geometry) might aid formation of spatial mental models, more so for piecemal strategists where flow of information is serial, like egocentric perspective. However, with no external frame around the spatial layout (circular geometry), participant is forced to use a more global representation with an allocentric perspective of the environment. Holistic strategy is predicted to be used more readily with circle-shaped environments.

How do spatial perspectives relate to cognitive strategies?

Whether spatial information derived from primary or secondary sources might lead to differences in mental representation remains in question. Siegel and White (1975)'s continuous development of spatial knowledge theory suggested that people can

create accurate mental representations of a novel environment by building blocks of knowledge. Landmark knowledge is the first stage where people observe salient objects or buildings in the environment. Route knowledge makes the connections between landmarks as sequential and procedural information comes in. Landmark and route are non-metric units, to their theory, and are built upon to form a more sophisticated level of knowledge, survey knowledge. Survey is a scaled version of the environment where information is metrically represented (Siegel & White, 1975). Whether spatial knowledge builds sequentially or simultaneously is still a question (Ishikawa & Montello, 2006), landmark and route knowledge are suggested to have non-metric sequential features (Allen et al., 1996). It should also be noted that to be able to create accurate cognitive maps relations between routes need to be metrically represented with an allocentric reference system.

To examine the individual differences in spatial knowledge, underlying spatial abilities were addressed (Allen et al., 1996; Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002; Ishikawa & Montello, 2006). Performance on descriptions of spatial environments showed individual differences. After learning a novel environment, men gave spatial descriptions mainly using metric (distance units) information and cardinal (north, south, etc.) directions, whereas women described the environment according to landmarks along a route (e.g., turn right from the grocery shop) (Lawton, 1994). More men used survey and more women used route strategies in way-finding tasks (Lawton, 1994). These individual variations have similarities to strategy differences in MR performance and neuroimaging literature showed evidence for distinctions between route and survey encoding (Shelton & Gabrieli, 2002). While encoding information from route

perspective activated areas that responsible for integration and updating of egocentric representations, survey encoding engaged areas processing objects (Shelton & Gabrieli, 2004). Thus, it would be reasonable to assume survey knowledge to have a global and holistic view, and landmark and route knowledge to use a more piecemeal strategy.

Map-reading in relation to MR and cognitive strategies

Cognitive-maps are created to represent spatial environments and the use of a survey perspective was sometimes suggested to be more effective in forming cognitive-maps (Thorndyke & Hayes-Roth, 1982). Landmark or route perspective, however, consist of sequential information and the person is required to form an inherently visual and holistic cognitive-map to make best use of this information.

Map reading has been investigated in regards to rotation ability. To read a map one needs to first localize, which requires aligning egocentric and allocentric views (Aretz & Wickens, 1992). Egocentric is the forward view of the self. The allocentric view, however, is a more world-centered view. Similar to cognitive processes in MR, in order to localize on a map one needs to rotate the global view of the map into congruence with the egocentric view. While simpler maps are easier to rotate and can be done so holistically, with more complex maps rotation as a whole became harder and the use of analytic piecemeal strategy is triggered (Aretz & Wickens, 1992). This finding corresponds with MR findings showing more analytic strategies as complexity increases (Just & Carpenter, 1985; Yuille & Steiger, 1982).

Strategy utilization with maps was further investigated. Researchers manipulated the nature of maps and presented participants with fragmentary and sequential maps as opposed to a whole map. In another condition, participants received verbal spatial

descriptions. Spatial descriptions were used to account for a secondary source of information, which is processed sequentially. The results suggest that even the maps were fragmentary and included a piece of the whole map, the representation of the fragments were similar to the representation of the whole map (Zimmer, 2004).

Do MR strategies match with room-size mental representation strategies?

Showing how people who use one strategy with MR also use a similar strategy with way-finding would strengthen the assumption that similar cognitive abilities underlie manipulable mental rotation tasks and larger-scale navigation. To test this, Pazzaglia and De Beni (2001; 2006) developed and used a Questionnaire on Spatial Representation. The questionnaire includes questions designed to understand whether an individual uses a survey, route or landmark-centered approach when learning new places. Males were found to perform better on both MR and way-finding task and to report mostly survey-based representational preferences. Women who were more survey-centered also did better on MR than their counterparts who reported using a more landmark or route centered approach to learning a new environment (Pazzaglia & De Beni, 2001).

In a recent study, Pazzagli and De Beni (2006) investigated the importance of the mental rotation process in creating perspective-free representations. For this, people went through an MR task and learned aligned and non-aligned schematic maps in a counterbalanced fashion, followed by directional judgment tasks. Mental rotation seemed to play an important role in the alignment effect with studies showing viewpoint-dependent spatial mental models via navigation (Shelton & McNamara, 1997; Mou & McNamara, 2002) and map-learning (Levine et al., 1982). If so, people with different

representational preferences would be expected to differ in their performance for aligned and non-aligned maps. Results supported this hypothesis. Low MR-scorers created representations affected more by the alignment. Whereas, participants who scored high on the MR task were less sensitive to the alignment effect suggesting the importance of MR in creating perspective-flexible mental models (Pazzaglia & De Beni, 2006).

Current research

We predict, with a series of experiments, that some underlying cognitive processes on small-scale (MR) and large-scale (accessing of room-size arrays from memory) spatial information processing are similar. The idea of rotating figures, objects, recalling configuration of array of objects or environmental layouts seem to share the same task: to rotate in the mind. Common findings on both MR and perspective taking would support our hypothesis.

One of the main findings of the MR tasks was the linear relation between angular discrepancy and performance measures (Shepard & Metzler, 1971). A number of studies found rather similar findings with perspective-taking tasks in navigation (Wraga et al., 2000) and angular disparity results showing the alignment effect with navigation (Diwadkar & McNamara, 1997; Shelton & McNamara, 1997; Mou & McNamara, 2002) and with maps (Boer, 1991; Pazzaglia & De Beni, 2006).

Our research question builds upon these previous findings and asks how strategy consistent stimuli and individual differences might play into these findings. Although these two tasks require some form of mental rotation, people use different strategies. While one might rotate the pieces another might rotate the image as a whole. Considering that the main findings of MR and navigation tasks mirror one another with the degree of

angular errors deviating from the mental representation, we hypothesize to see further corresponding results with the use of different strategies among MR and room-size arrays. Individuals who apply holistic and piecemeal strategies with MR might show differences that parallel with acquiring spatial knowledge from a primary source such as navigation. To include larger-scale environment learning means incorporating learning from different sources. We predict that spatial information, as long as it is learned well, gathered from direct experience or maps or mentally rotating figures would show similarities in representations.

We conducted four experiments. The first experiment investigated the use of strategies between individuals on a typical 3-D MR task where stimuli are modified to afford a particular strategy. The second experiment used 2-D abstract and complex figures. Typical whole figures might be more fitting for holistic strategists, thus we introduced "cut" figures to examine how strategy-consistent stimuli affects MR. To incorporate the use of strategies with learning source of room-size arrays participants either learned layouts of objects as whole-arrays or half-array at a time. Whole figure processing is expected to be faster and more accurate. It might be, however, different for whole-array rotation because it would require encoding and recalling configuration of a full-array of objects, which is a hard task.

We also introduced a form of framing in four experiments to provide additional spatial information. In Experiments 1 and 2, with mental rotation task, we framed the figures with rectangular structures. In Experiments 3 and 4, with room-size arrays, we relied on room/map geometry for framing. Participants learned arrays either within a circular or rectangular room via direct experience or from circular or rectangular maps testing the

effect of environment geometry on overall representations and strategies. Rectangular geometry is proposed to help with array performance from memory. We suggest that framing would also benefit mental rotation task. Since frame provides environmental cue, or reference point, it might help, especially those who use piecemeal strategy. For those who are holistic rotators and use more global representations, performance should not be affected by the existence (or lack) of a frame. However, it is also possible that framing might affect rotation of cut figures or half-arrays differently. With cut figures, rotating the figures in halves might be hard and increasing additional information might be hindering the process rather than helping because of the increased complexity and cognitive load. With rotation of room-size arrays from memory, learning source might interact with geometry as well as whole- and half-array learning. While circular geometry is suggested to force a global or survey-like representation, learning whole-arrays might be easier whereas rectangular structure with a whole-array full of objects can tax on the cognitive load and keeping half-arrays in memory might be easier.

Experiment 1

Mental rotation (Shepard & Metzler, 1971) performance frequently shows individual differences (Linn & Petersen, 1985; Voyer & Bryden, 1990) suggested to stem from different cognitive strategies used to solve MR problems. One such strategy difference, whether rotating objects holistically or piecemeal, has been proposed to account for mental rotation gender differences by suggesting that males rely more on a holistic strategy and females adopt a piecemeal approach (Kail et al., 1979; Yuille & Steiger, 1982). Mental Rotation tasks use standard, “whole”, object pairs which can be

cognitively sub-divided to adopt a piecemeal strategy. Previous, unpublished work in our Spatial Cognition lab (Naylor et al., unpublished data) added cut figures to encourage use of a piecemeal strategy. If people adopt different, either holistic or piecemeal strategies, might stimuli matching their strategy differentially impact performance relative to strategy-inconsistent stimuli? Performance difference on MR task have also been tied to decision making processes, suggesting a greater tendency for females to double check same/different judgments and a greater tendency for males to guess (Voyer et al., 2004; Voyer & Saunders, 2004). Mental rotation judgments and cognitive strategy differences might also be affected by other stimulus characteristics, such as the presence of a frame that can be used as a reference. People who use piecemeal strategy in mental rotation might benefit from this framing more so than people who use a holistic strategy because they would have a reference point to represent information. Broadly, this experiment investigates strategies, decision making, and the availability of an external frame.

Method

Participants

One hundred two Tufts undergraduates, 46 females and 56 males, participated for partial course credit.

Materials

Mental rotation stimuli. Stimuli consisted of 3-dimensional cube figures (Shepard & Metzler, 1971) were created using CAD software. Each contained eleven to twelve cubes arranged to form three different figures with 90 degree angular projections into 3-D space. These original 3-D block figures comprised the whole figures. Cut figures resulted from dividing these original figures into two parts (one half with 5 cubes and the other

with 5 or 6) and separating the halves by 0.75 inches (Naylor et al., unpublished data). All figures (whole and cut) were rotated in 30-degree-increments, with a total of seven rotations: 0, 30, 60, 90, 120, 150, and 180, and were done so in X, Y, and Z axes. Mirrored versions of each figure at each rotation were also created. Stimulus pairs consisted of two whole figures or two cut figures (Figures 1-1a and 1-1b) that were either the same (rotated version) or different (mirror image) of one another. A vertical line separated the two figures in a pair. For framed stimuli, rectangular frames, approximately 5.93 inches X 4.03 inches surrounded each whole figure, and both halves of each cut figure. Approximately half of the participants saw framed objects.

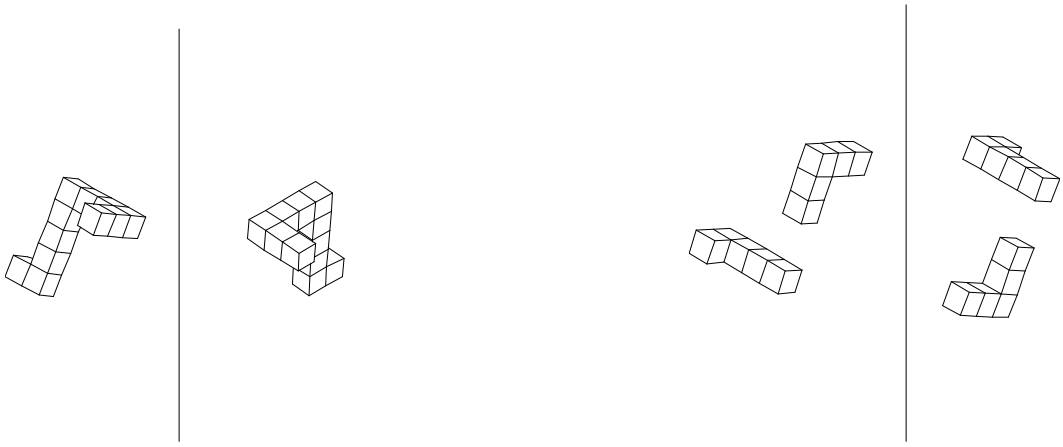


Figure 1-1a (above left) displays a pair of whole figures while *b* (above right) shows a pair of unfamed cut figures.

Individual differences questionnaire. An individual differences questionnaire asked participants about gender, familial sinistrality, self-rated sense of direction, and preference for spatial information format (map or verbal directions).

Mental Representation Questionnaire. The mental representation questionnaire (Pazzaglia & de Beni, 2001) investigates sense of direction and spatial perspective preferences. In this questionnaire, participants rated how they rotate themselves in an

environment, and their mental representation of environment in various settings such as inside a building or in an open space (see Appendix A).

Procedure

The experiment took place in Spatial Cognition Lab at Tufts University. Participants completed the experiment with either unframed or framed stimuli. All participants for the unframed group completed the experiment before the framed group. After consenting to take part, participants sat in front of a computer running Superlab™ software. They read instructions from the screen describing the two-part response paradigm. With this paradigm, participants, on each trial, first view a fixation cross and then see the same mental rotation pair twice in succession. The first time they see the pair they are to hit the space bar when they know whether the figures are the same or mirror images. This will be referred to as the *know* response. After hitting the space bar the same pair appears and participants provide their response (*same* or *different*). This will be referred to as the *answer* response. Participants progressed through trials at their own pace. The experiment was divided into two blocks (whole figures and cut figures) that were counterbalanced across participants. Each block contained 63 trials, with a total of 126 MR problems. Participants could take a break after each block, if they desired.

After completing both experimental blocks, all participants received the Individual Differences questionnaire. Participants in the framed group also completed the Mental Representation Questionnaire.

Results

Coding and Analysis

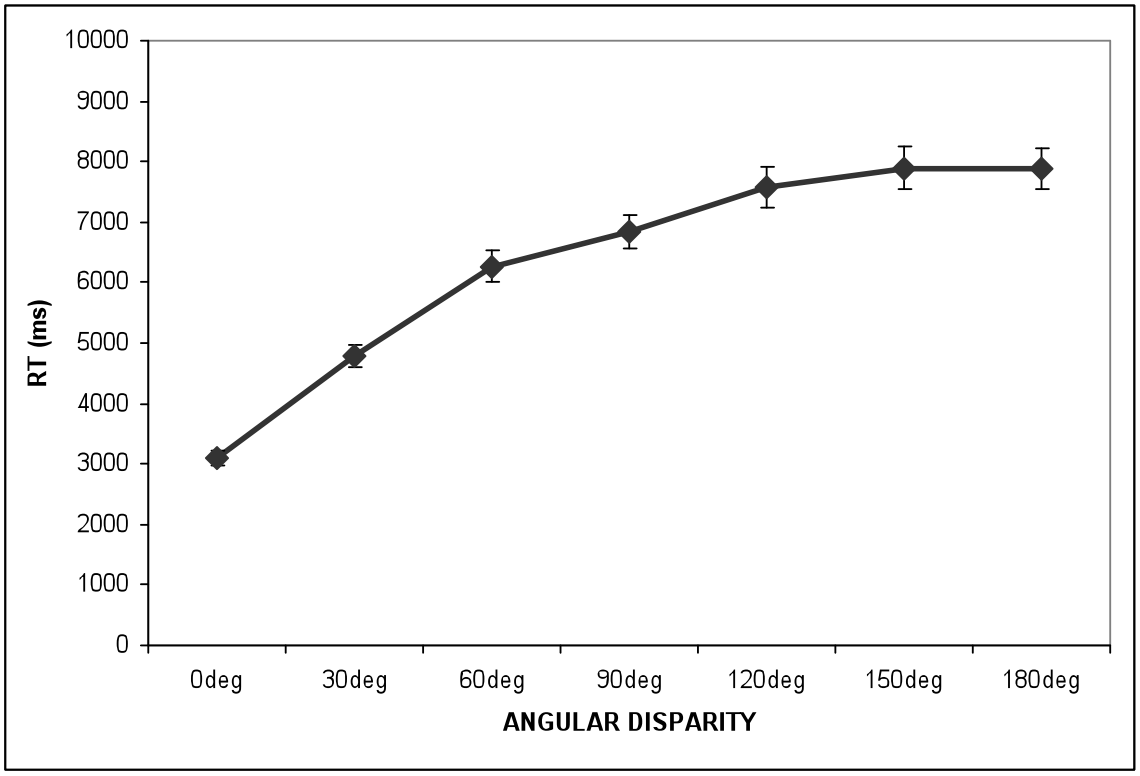
Data included reaction time (RT) to the *know* response, and *accuracy* and RT of the *answer* response. RT to the *answer response* assessed the extent to which participants engaged in double-checking. Only correct responses and their corresponding reaction times were included in the analysis. Given the high response variability, data were trimmed by eliminating participant's highest and lowest *know* RT and accompanying *accuracy* and *double checking* RT (Bush, Hess, & Wolford, 1993). Data from 7 people were eliminated because they did not follow the instructions properly.

Angular Disparity (0, 30, 60, 90, 120, 150, and 180), and Figure Consistency (whole, cut) were within-participant variables. Frame (unframed, framed), Gender (male, female), Preference (map, verbal), and Mental Representation (survey, landmark) served as between-participant measures of primary interest. Gender, Preference, and Mental Representation were grouped under individual difference measures and were examined separately.

Statistical assessment used repeated-measures analysis of variance (ANOVA). ANOVAs on *know RT,* and answer *accuracy* data used a 2 (Figure Consistency) X 7 (Angular Disparity) X 2 (Frame) mixed-factorial design. We first reported results of this omnibus ANOVA. Then we included 2 (Gender), and 2 (Preference) variables into the analysis one by one. Each section related to these individual difference measures will only report additional results to the omnibus ANOVA. Finally, the effect of Representation could only be assessed for framed trials. We reported only results of the

know RT, and answer *accuracy* data. The *answer RT* data would uncover "double-checking" behavior, but showed no such evidence.

Mental rotation performance was first evaluated as a function of angular disparity for *Know* response (RT) and *accuracy* (correct percentage) data. The results showed that angular disparity affected MR response such that as angular disparity increased RT increased, F (6, 558) = 135.901, $p < .001$, MS_e= 4538917.6 (Figure 1-2a) and accuracy decreased, F (6, 558) = 55.763, $p < .001$, MS_e= 174.019 (see Figure 1-2b).



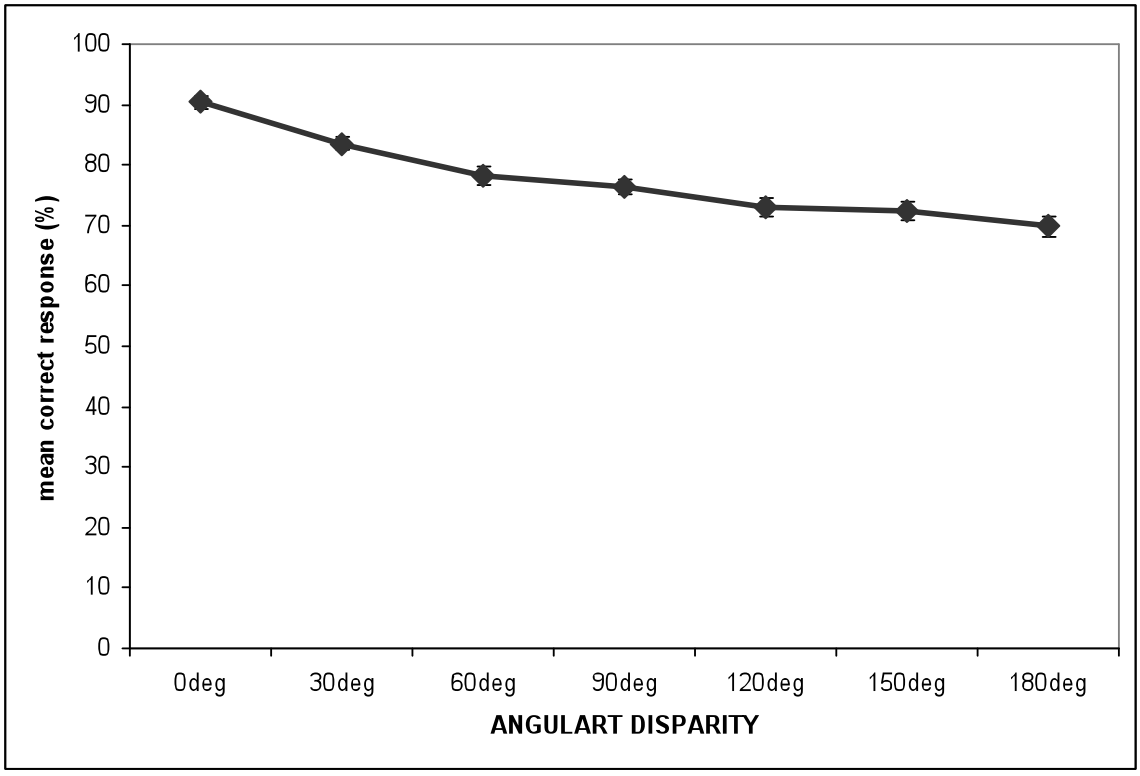
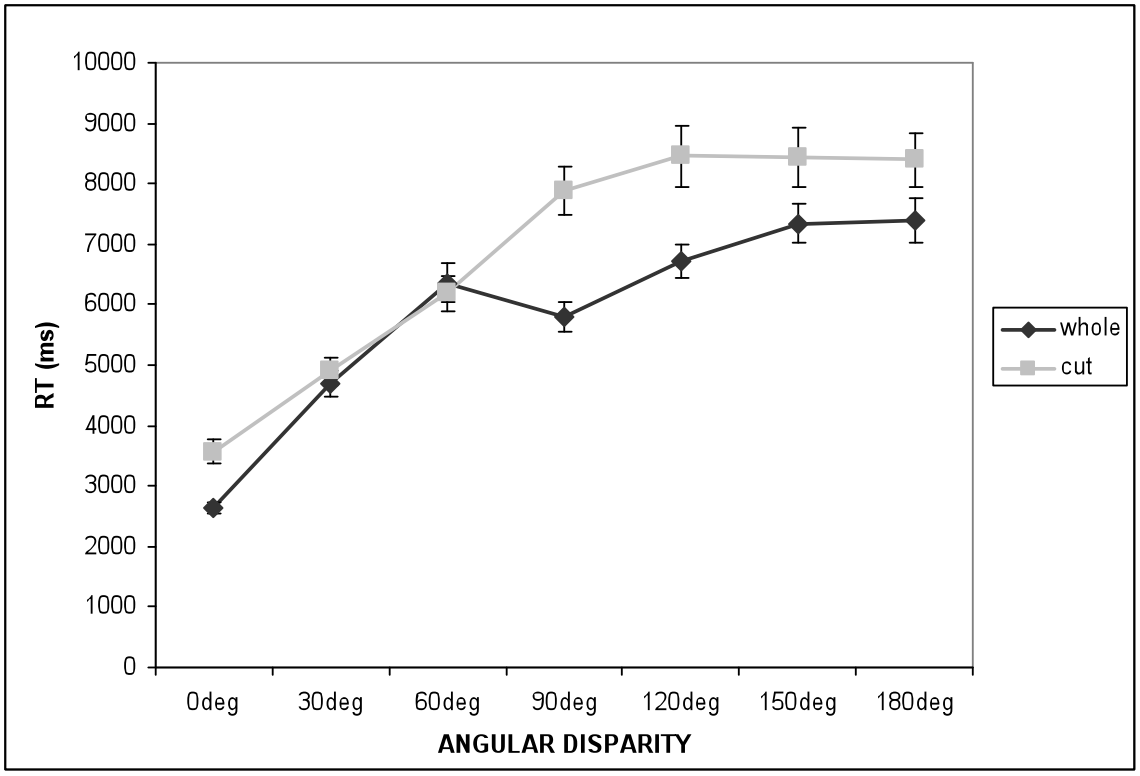


Figure 1-2 shows Data on both *Know* RT (1-2a; top) and accuracy (1-2b; bottom) as a function of Angular Disparity.

The analysis showed an effect of Figure Consistency, F (1, 93) = 15.141, p < .001, MS_e= 21289958.61. Participants responded faster to whole (M = 5847.51 ms) than cut objects (M =6832.19 ms). They were also more accurate to whole (M = 82.25 %) than to cut objects (M = 73.17 %), F (1, 93) = 53.707, p < .001, MS_e= 510.032.

Figure Consistency interacted with Angular Disparity with *know* RT, F (6, 558) = 9.253, p < .001, MS_e= 3211700.888, and with *accuracy* data, F (6, 558) = 10.054, p < .001, MS_e= 151.148. For small (0, 30, 60) degrees of rotation, participants rotated whole and cut figures equally fast whereas at greater angular disparities they rotated whole figures faster (see Figure 1-3a) and more accurately (Figure 1-3b).



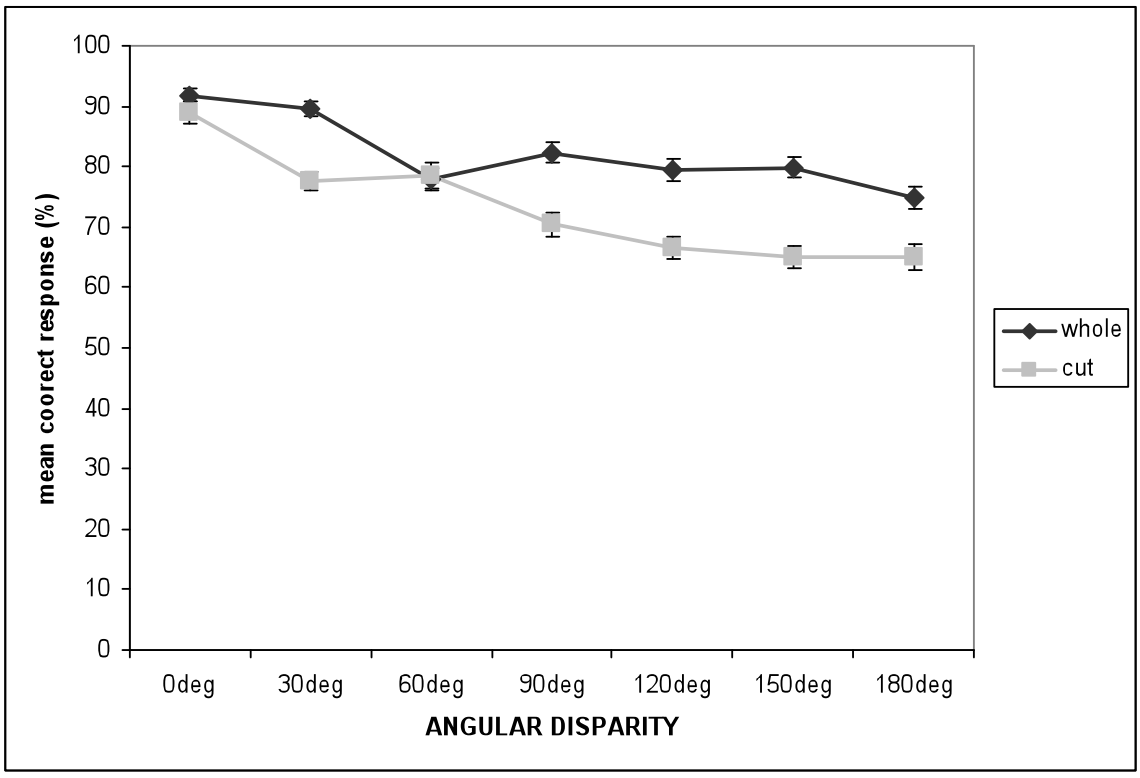


Figure 1-3. Response times (1-3a: top) and correct percentages (1-3b: bottom) to whole and cut figures on degrees of rotation.

Framing did not affect mental rotation performance by itself, but did show a three-way interaction between Frame X Figure Consistency X Angular Disparity with RT data, F (6, 558) = 2.555, $p < .05$, MS_e= 3211700.89. For framed stimuli, participants showed similar response times to whole and cut objects for small angular differences (0^0, 30^0, 60^0) and faster response times for whole objects with greater angular differences (> 60^0). However, for unframed stimuli, performance gap between whole and cut figures closed at the greatest levels of angular disparity, i.e., 150^0 and 180^0.

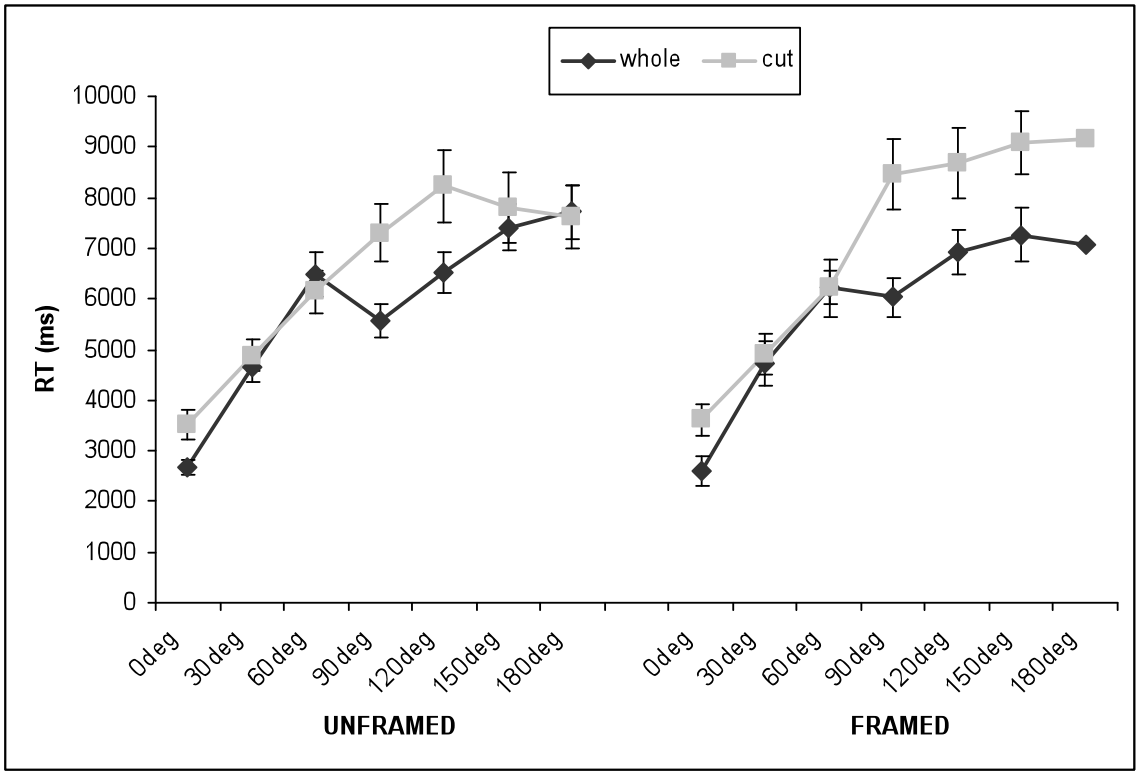


Figure 1-4. Performance to whole and cut figures over degrees of rotation are shown as a function of frame with know RT. *Figure 1-4* (left section) depicts un-framed response times and *Figure 1-4* (right section) shows responses to framed stimuli.

Individual Difference Measures

Gender. With Gender in the analysis, results showed a gender main effect for both RT and accuracy. Females responded slower (M= 6963.67 ms), F (1, 91) = 5.269, $p < .05$,

MS_e= 76852428.95, and less accurately (M= 73.69 %), F (1, 91) = 10.899, p = .001, MS_e= 1532.638 than males (M_{RT}= 5851.15 ms; M_{acc}= 80.83 %).

Know RT data showed an interaction between Gender X Angular Disparity, F (6, 546) = 2.199, $p < .05$, MS_e= 4497288.02. Females and males responded equally fast for small angular disparities (0^0 and 30^0), but males responded faster for angular disparities greater than 60^0 (Figure 1-5).

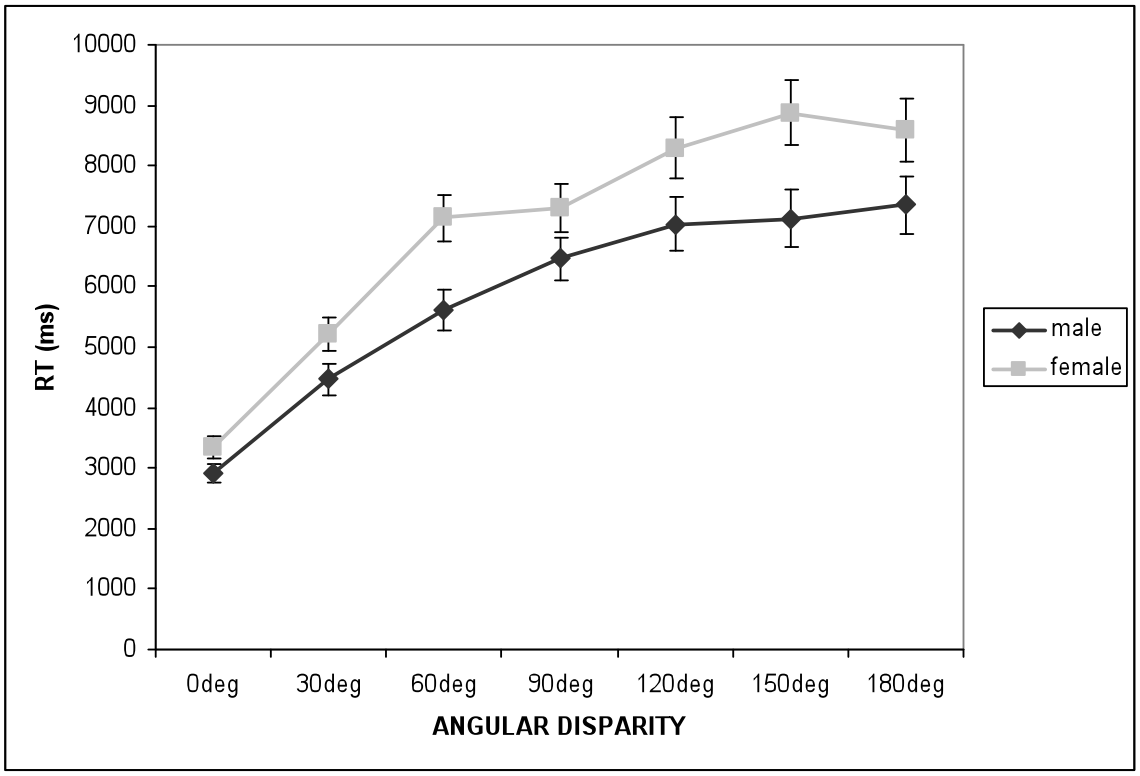
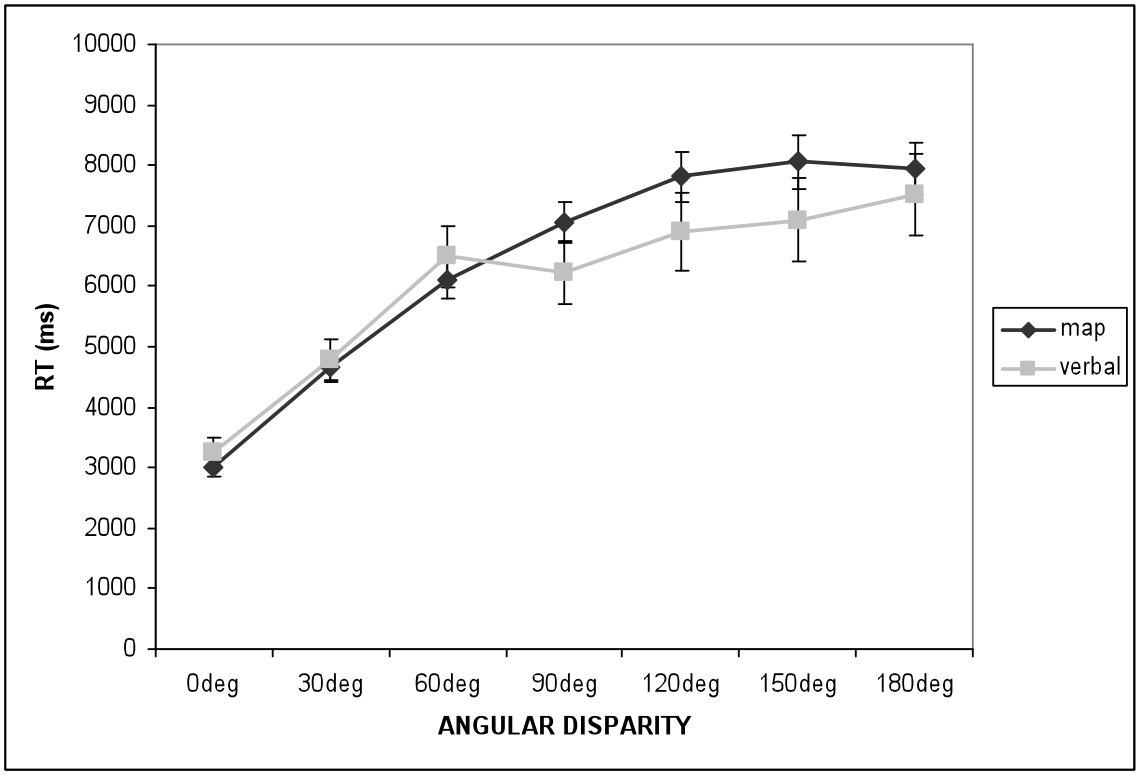


Figure 1-5. RT interaction between gender and angular disparity.

Spatial Information Preference (henceforth referred to as Preference) variable reflects people's self-descriptions of how they prefer to learn spatial information--via maps or verbal descriptions. *Map preference* participants responded more accurately (M = 81.53 %) than *verbal preference* participants (M = 69.24 %), F (1, 88) = 30.953, $p < .001$, MS_e= 1270.918.

Know RT showed a Preference X Angular Disparity interaction, F (6, 528) = 2.82, p = .01, MS_e= 4402786.57. Verbal preference participants responded faster than Map preference participants for angular disparities greater than 60º (see Figure 1-6a). Accuracy data showed this same interaction, F (6, 528) = 5.751, p < .001, MS_e= 166.01. Verbal preference participants responded less accurately than map preference participants, particularly at greater angular differences (Figure 1-6b). There might be a speed-accuracy tradeoff for Verbal and/ or Map preference.



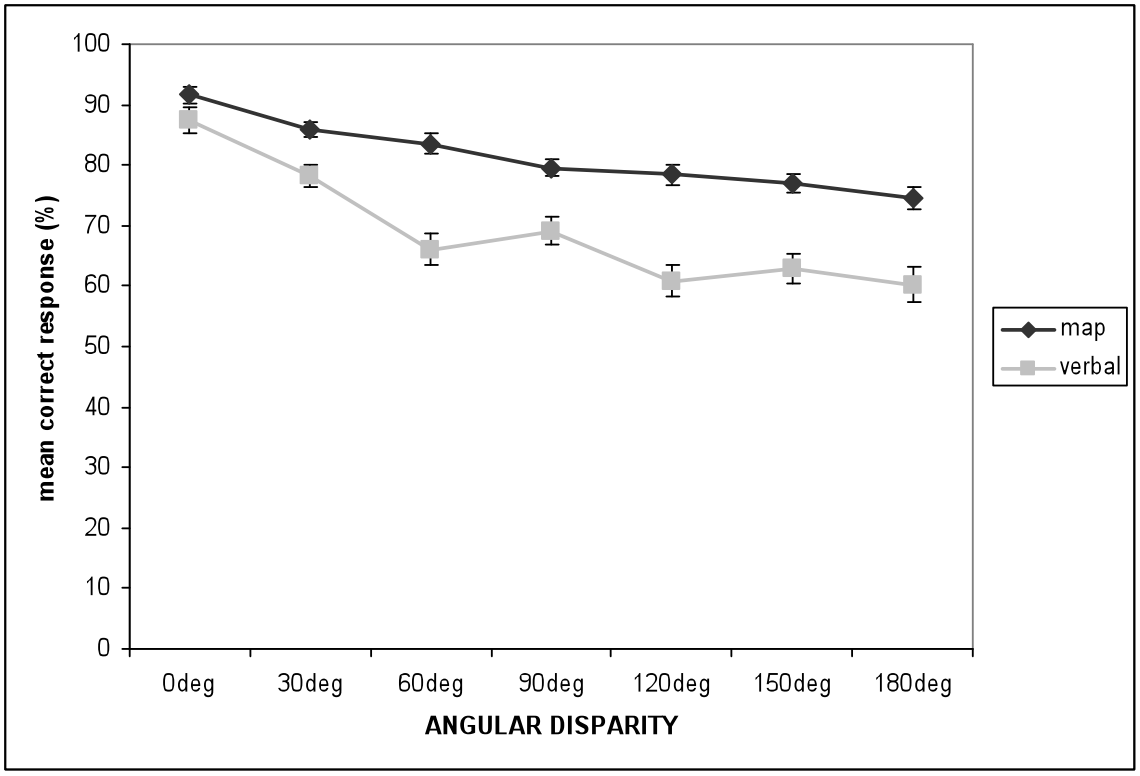


Figure1-6. Preference by Angular Disparity for know RT (1-6a: top) and accuracy (1-6b: bottom).

With the addition of Preference variable to the analysis, the analysis showed a Figure Consistency X Frame interaction for *RT* data, $F\,(1, 88) = 5.37$, $p < .05$, $MS_e = 19930081.12$. When there was no frame around the stimuli, performance to whole and cut figures were equally fast, whereas with a frame, "cut" figure performance slowed down (see Figure 1-7).

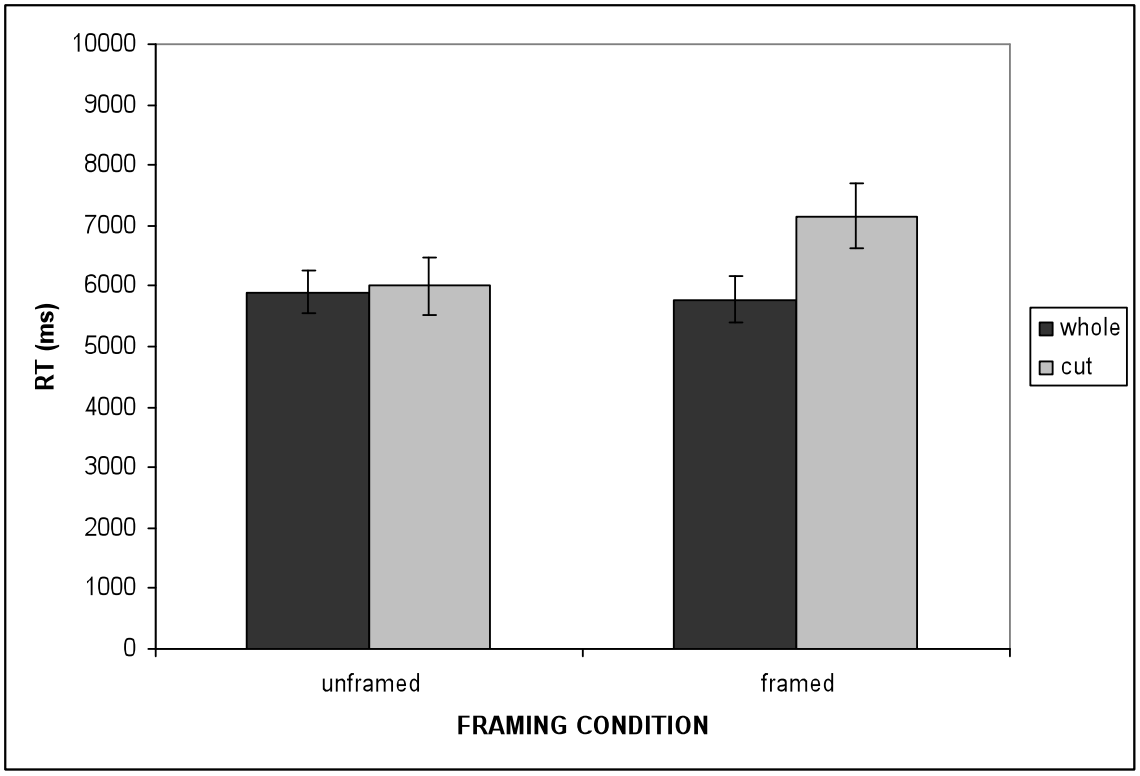


Figure 1-7 shows response rates to whole and cut figures when they are unframed or framed.

The *RT* data showed a marginal three-way interaction between Preference X Figure Consistency X Frame, F (1, 88) = 3.747, p =.056, MS_e= 19930081.12. People who preferred maps rotated whole figures faster than cut ones regardless of a frame. Whereas people who preferred verbal directions, rotated cut figures faster than whole ones when stimuli did not have frame, but rotated whole figures faster when stimuli were framed. (see Figure 1-8). Moreover for verbal preference, framed "cut" stimuli led to slower rotation than unframed "cut" rotation (Figure 1-8).

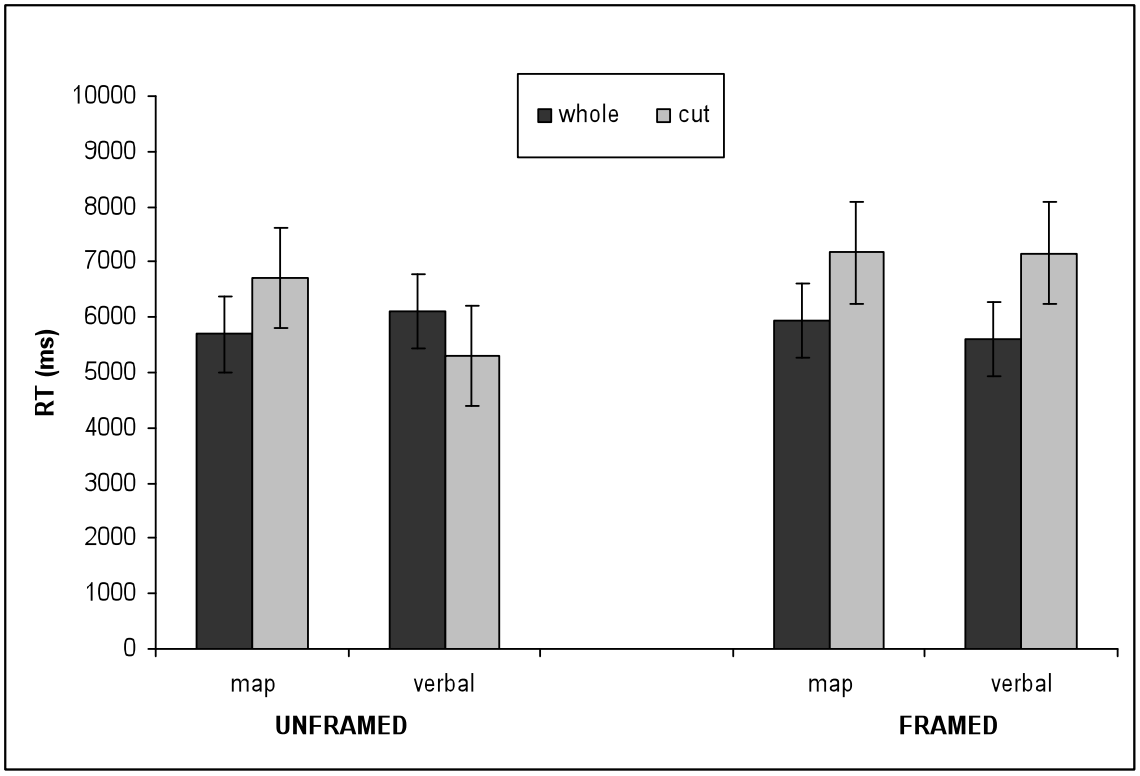


Figure1-8. Preference and Figure Consistency performance is shown for Un-Framed (left section) and Framed (right section) conditions.

Mental Representation (henceforth referred to as *representation)* questionnaire data was only available for participants who viewed framed objects. We coded survey-centered compared to landmark-centered as described (Pazzaglia & DeBeni, 2001). Survey-centered people responded faster (survey: 5410.71 ms; landmark: 7374.43 ms), F (1, 45) = 8.433, $p < .01$, MS_e= 7437352.28. Representation interacted with Angular Disparity for *know* RT, F (6, 270) = 2.852, $p = .01$, MS_e= 4433794.469. Landmark-centered participants' RT increased more as a function of angular difference than did survey-centered participants (see Figure 1-9).

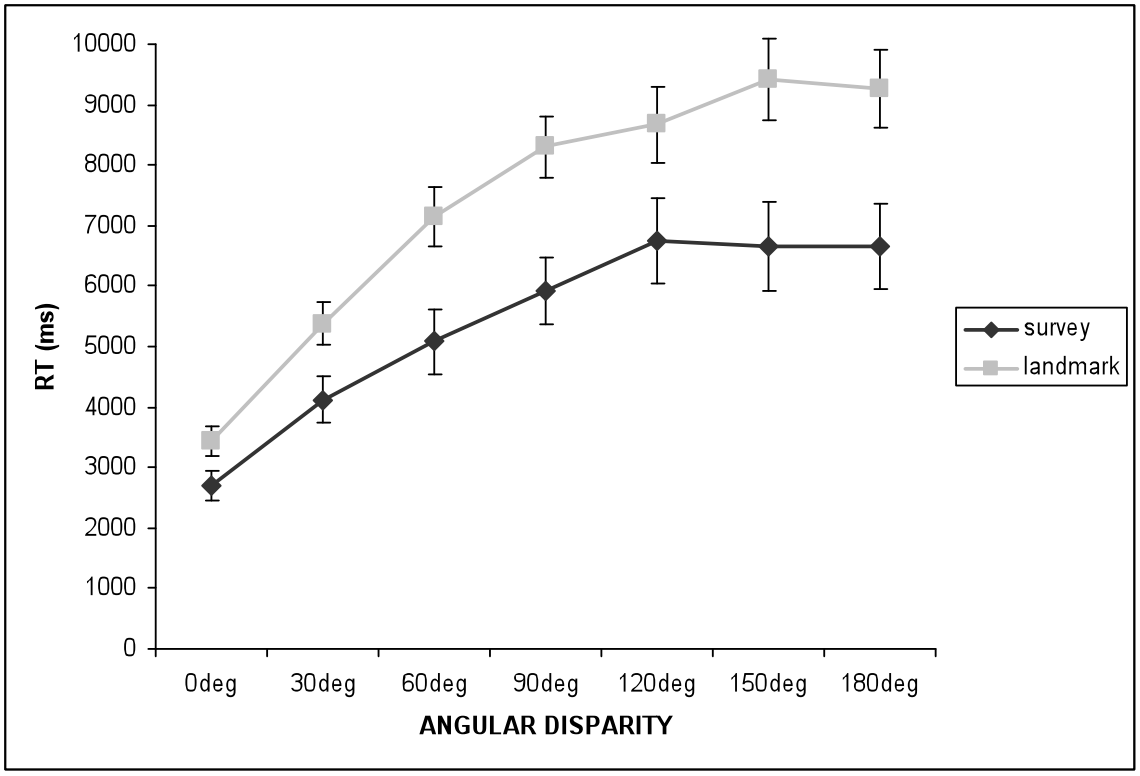


Figure 1-9 displays the affect of Representation on Angular Disparity for the *know* response.

Discussion

Consistent with the literature, participants were slower and less accurate to decide whether a pair of 3-D figures was the same or different from one another as the degrees of rotation between pairs increased, showing an angular disparity effect (Blough & Slavin, 1987; Collins & Kimura, 1997; Cooper, 1975; Heil & Jansen-Osmann, 2008; Kail et al., 1979; Maccoby & Jacklin, 1974; Shepard & Metzler, 1971). Extending MR research, we added "cut" versions of the "whole" figures to promote strategies that have been suggested to account for individual differencess in MR performance; holistic and piecemeal. Further, we explicitly examined individual differences (i.e., gender, preference, and representation style) to make a comparison to performance with strategy-consistent stimuli.

"Whole" figures, overall, generated faster responses than "cut" figures. Moreover, whole vs. cut pattern was indicative of holistic vs. piecemeal processing that was shown when in an interaction with angular disparity. Individual difference measures were similar to whole vs. cut findings. In other words, the difference among variables (figure consistency, gender, preference, representation) was more pronounced with greater angular disparity between the figures, showing the pattern used to suggest strategy differences in the first place (Kail et al., 1979). Experiment 1 showed that patterns of holistic and piecemeal rotators were similar to one another (e.g., “male” and “survey” mimicking “whole” rotation pattern, and “female” and “landmark” mimicking “cut” rotation pattern). To our knowledge, this finding is new to the literature. Preference pattern was the opposite of what we expected. Performance gap between people preferring map and verbal preference widened with greater angular disparity, however, the pattern favored “verbal” preference. This is not consistent with our prediction, but the possible speed-accuracy tradeoff makes it difficult to interpret.

The existence (or lack of) a frame around the figures, moreover, interacted with the pattern indicating a holistic vs. piecemeal approach. Framing hindered performance of rotation of “cut” figures that were consistent with piecemeal-strategy. Preference findings showed similar results. While participants preferring maps rotated “whole” figures faster and ones preferring verbal descriptions performed better with “cut” figures, having a frame affected “cut” performance, more so for verbal preference. As hypothesized, piecemeal-strategy was affected by frame. Cut figures were introduced as a means to enforce piecemeal strategy use. And verbal preference people were more likely to rely on piecemeal strategies in mental rotation. Combined together, piecemeal rotators

when presented with strategy-consistent stimuli were affected negatively with the existence of frame.

Experiment 2

Stimulus complexity has been shown to affect MR task performance (Bauer & Jolicoeur, 1996; Peters et al., 1995; Yuille & Steiger, 1982). Women, who showed a disadvantage with 3-D figures, were much faster with 2-D objects, whereas males were more accurate with 3-D images compared to 2-D ones (Bauer & Jolicoeur, 1996; Peters et al., 1995). With more complex stimuli, holistic rotation was reported to be a more efficient strategy (Corballis, 1997). This experiment examined performance of 2-D complex figures as a function of framing and strategy-consistent-stimuli and how individual differences (i.e., gender, preference, and spatial representation) play into these factors. Similar to Experiment 1, we used whole and cut versions of 2-D abstract polygons to engage holistic and piecemeal strategies, respectively. Would people who preferred maps and were survey-centered be more global and holistic rotators that those who preferred verbal directions and relied on landmark representations, regardless of the figure consistency? Furthermore, how would frames surrounding the figures affect rotation and would this effect be the same for whole and cut figures? Experiment 1 showed that framing made 3-D objects faster to rotate. Experiment 2 used frame as a within-participant factor to directly compare the effect of framing on rotation performance. In Experiment 1, we also tested whether females double-checked their answers (Voyer et al., 2004; Voyer & Saunders, 2004), since we found no evidence of this we did not use the double checking paradigm with this experiment.

Method

Participants

Thirty-eight Tufts University students (28 female, 10 male) participated for partial course credit. None of them participated in the previous experiment.

Materials

Mental rotation stimuli. Two-dimensional stimuli were created using Canvas Software and served as the *whole figures.* Six, asymmetric objects were created by connecting the dots of a 9-dot diamond configuration and filling the resultant *whole* figure with a gradient-dot texture (see Figure 2-1a). Each object was then rotated in 30-degree increments from 0 to 180 degrees and each rotation was mirror-reflected. *Cut figures* were created dividing the whole figures approximately in half. To determine the best way to cut each figure, nine pilot participants indicated for each figure the best way to cut it in half. All responses were collapsed together for each figure and most frequently used solution was applied. These half parts were also filled with gradient-dot texture and put approximately 0.75 inches (Figure 2-1b) apart from one another to emphasize that they are two halves of a whole figure.

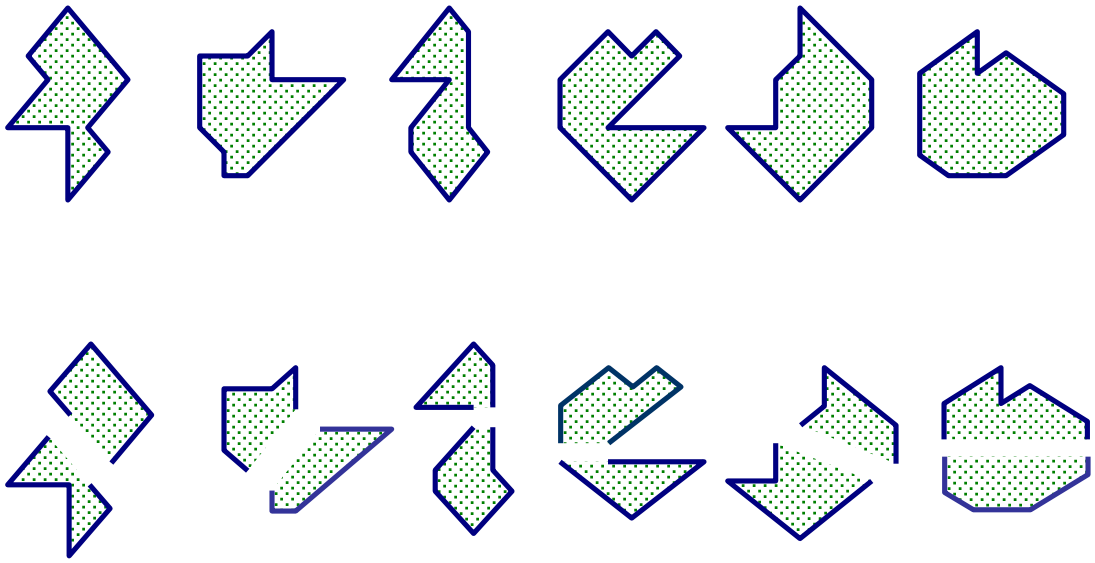


Figure 2-1a (top section) shows six of the asymmetric whole objects and *Figure 2-1b* (right above) depicts their cut versions.

After creating the individual stimuli, they were paired to form same or mirror-reflection combinations. Objects in a pair were separated from one another with a vertical line. Pairs were either framed or unframed. For framed pairs, similar to Experiment 1 rectangular frames, surrounded each whole figure (Figure 2-2a), and both halves of each cut figure (Figure 2-2b). In total there were 84 whole and 84 cut trials for framed and unframed blocks, totaling 336 trials. Of the 84 whole and cut pairs, 42 were the same and 42 were mirror images. Each rotation degree was represented 12 times.

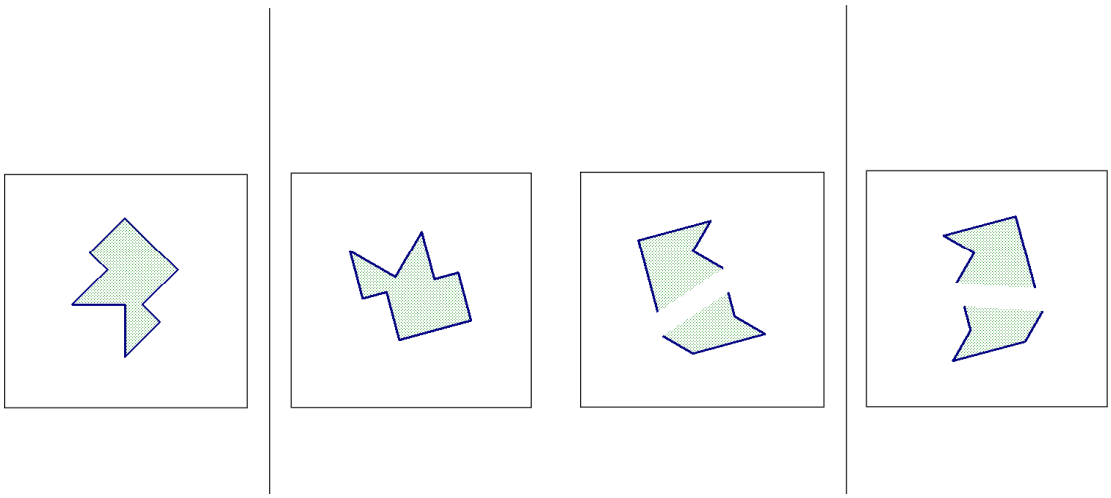


Figure 2-2a (left) is an example of a framed whole pair where the pair is 120-degree rotated from one another yet the "same". *Figure 2-2b* (right) depicts an example of a framed and 30-degree-rotated mirror-reflection making the cut pair "different" from one another.

Questionnaires. The individual differences and spatial mental representation (Appendix A) questionnaires used in Experiment 1 were again used.

Procedure

The procedure was similar to Experiment 1, with some modifications. After consenting to take part in the experiment, participants were seated in front of a computer. They read instructions on the monitor before beginning. Trials were presented in two blocks, whole and cut, counterbalanced across participants. For one block, they saw either framed or unframed, again counterbalanced. On an individual trial, participants first saw a fixation cross for 500 ms, followed by a pair of figures that are either the same, but rotated (see Figure 18a), or mirror reflections of one another (see Figure 18b). Unlike Experiment 1, the stimuli pairs appeared only once and participants responded “same” or “different” at this first presentation. After the computerized MR task they completed the individual differences questionnaire followed by the spatial mental representation questionnaire.

Results

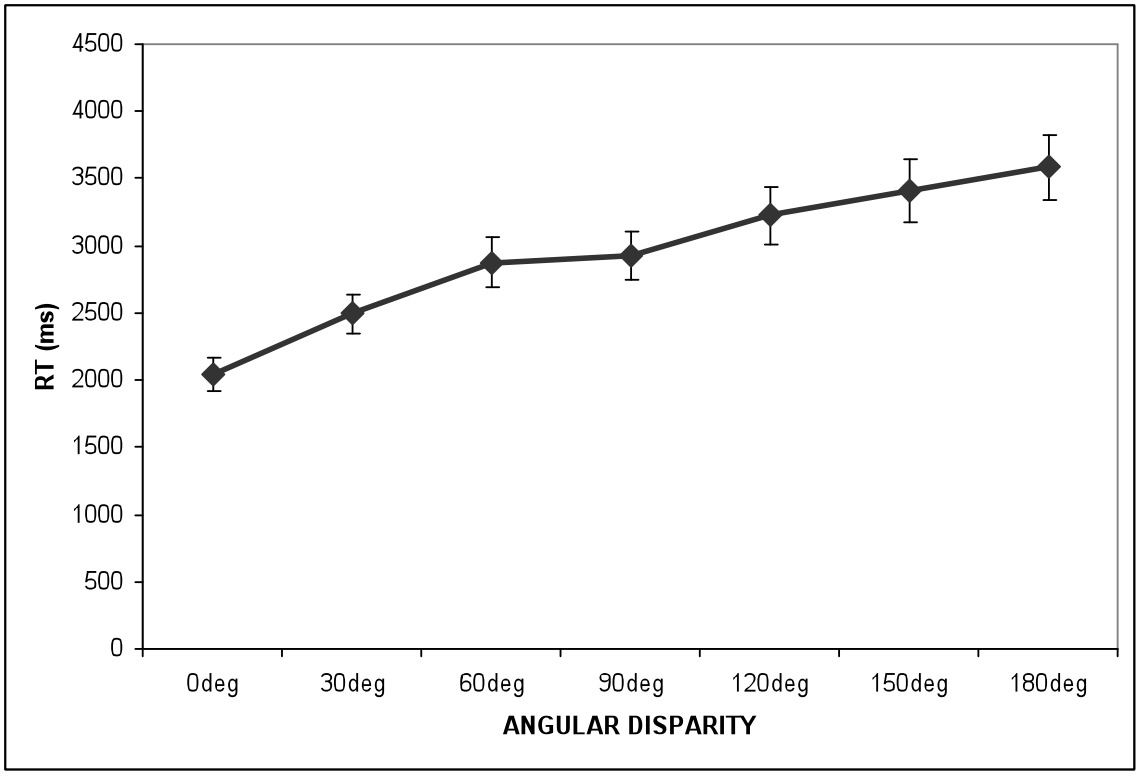
Coding and Analysis

Dependent measures included *accuracy* and reaction time (RT) to 2-D mental rotation problems. Given the high response variability, data were trimmed by eliminating participant's highest and lowest RT at each angular disparity (Bush et al., 1993). Data from 8 people were eliminated because they did not follow the instructions properly. Only correct responses and corresponding RTs were included in the analyses. Mean percentage for each participant was calculated from the accuracy data.

Angular Disparity (0, 30, 60, 90, 120, 150, and 180), Figure Consistency (whole, cut), and Frame (unframed, framed) served as within-participant factors. Individual difference measures, including Gender (male, female), Preference (map, verbal), and Mental Representation (survey, landmark) served as between-participant factors of primary interest. These were analyzed separately by adding each, one by one, to the omnibus ANOVA.

Repeated-measures analysis of variance (ANOVA) on mean correct response and RT data was conducted first with 2 (Figure Consistency) X 7 (Angular Disparity) X 2 (Frame), then adding [2 (Gender), 2 (Preference), or 2 (Mental Representation)] into the analysis. We first reported the results of the omnibus ANOVA followed by any additional results with the individual difference measures.

Results showed the standard MR finding (e.g., Cooper & Shepard, 1973) of an increase in RT, F (6, 210) = 60.743, $p < .001$, MS_e= 678516.46, and decrease in accuracy, F (6, 216) = 17.304, $p < .001$, MS_e= 183.202, with increased angular disparity (see Figures 2-3a and 2-3b).



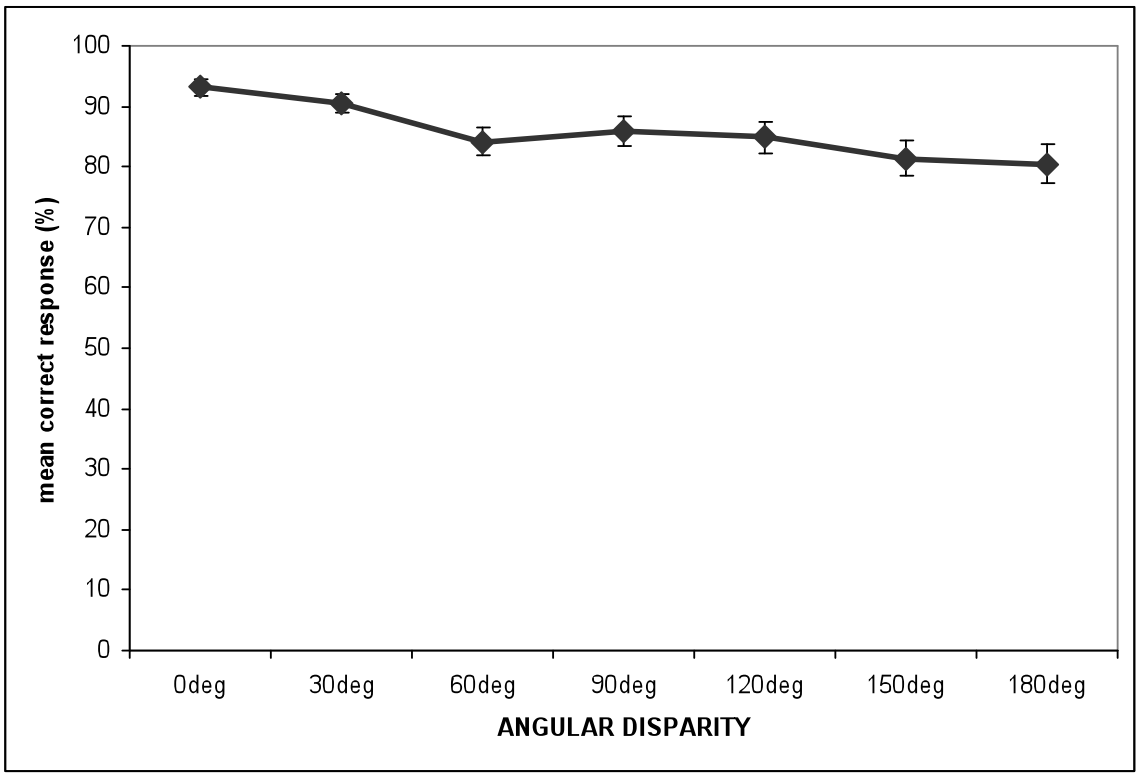


Figure 2-3a (top) shows angular disparity on RT data and *b* (bottom) on accuracy data.

The effect of whole vs. piecemeal stimuli on MR performance assessed by Figure Consistency did not show main effects with RT or accuracy data. However, the accuracy data showed an interaction of Figure Consistency X Angular Disparity, F (6, 216) = 2.237, $p < .05$, MS_e= 79.92. Accuracy did not seem to differ for whole and cut figures, except "whole" figure rotation was slightly more accurately judged at 60^0, 90^0, and 180^0 whereas "cut' figures were more accurately judged at 120^0 (see Figure 2-4). RT data did not show the same effect, but interacted with Frame, which is explained below.

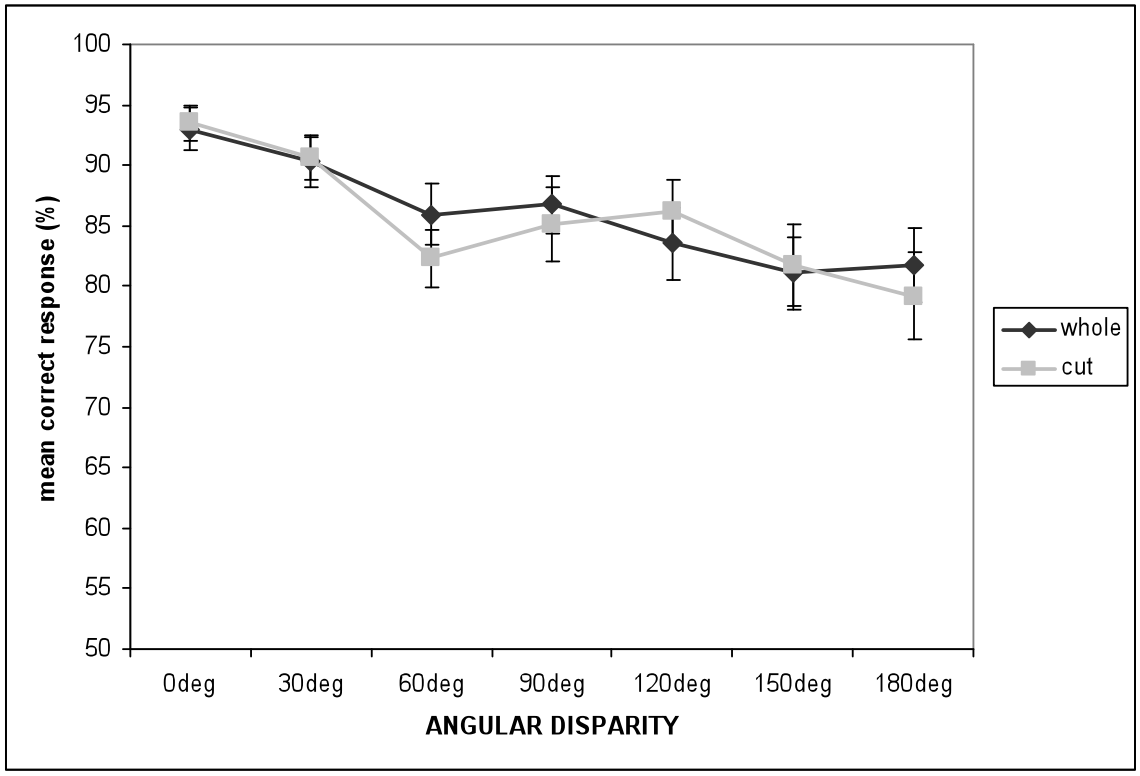


Figure2-4. Rotation of whole and cut 2-D figures as a function of Angular Disparity with accuracy data.

Framing the figures did not affect overall performance. RT data showed a Frame X Figure Consistency interaction, F (1, 35) = 6.29, $p < .05$, MS_e= 1833569.84 (Figure 2-5). Framing hindered processing of whole figures. While rotation of whole figures was faster when stimuli did not have a frame, cut figure rotation was as fast as with or without a frame.

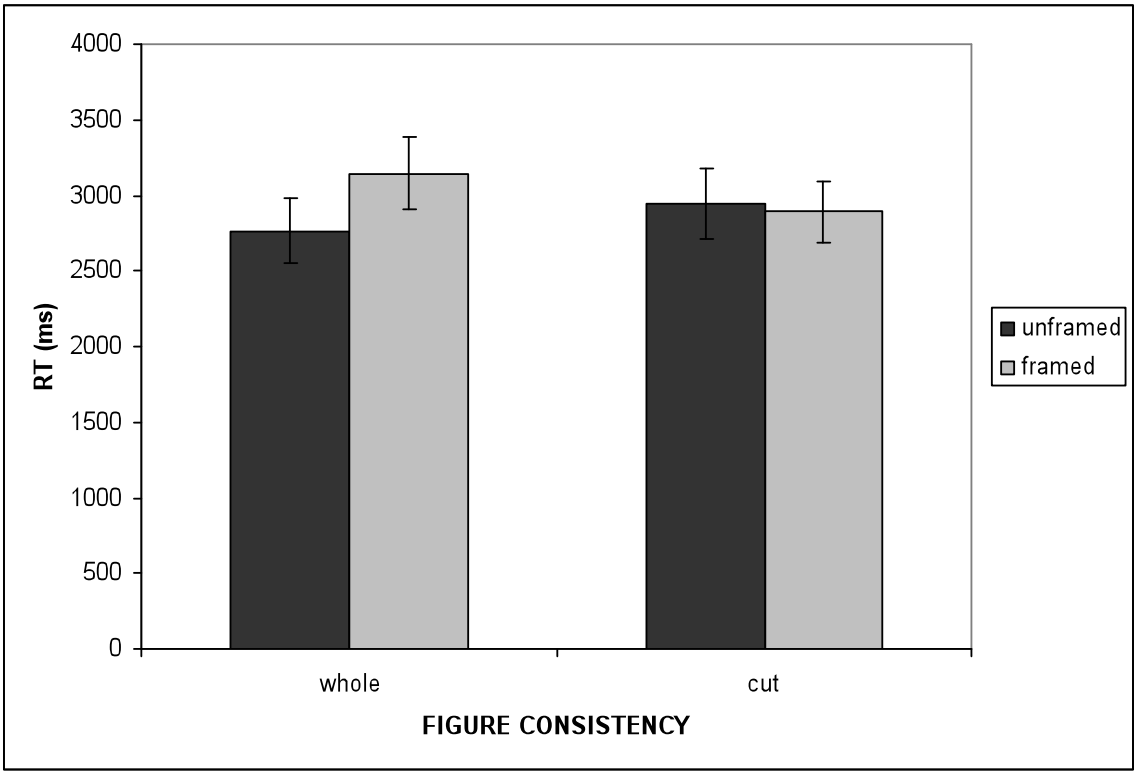


Figure 2-5 shows how the existence (or lack) of a frame around the figures affected whole and cut figure rotations with RT data.

Both RT and accuracy data showed a three-way interaction between Frame X Figure Consistency X Angular Disparity, F (6, 210) = 2.883, p = .01, MS_e= 291294.08, and F (6, 216) = 3.108, p < .01, MS_e= 97.01, respectively. The previously described two-way interaction was more pronounced as angular disparity increased. When stimuli were unframed "whole" figures generated faster responses at each degree of rotation, whereas for framed stimuli, "whole" figures were slower than "cut" figures and the difference was more pronounced with greater angular disparity (see Figure 2-6). Accuracy data did not vary systematically with framing and figure consistency (see Figure 2-7).

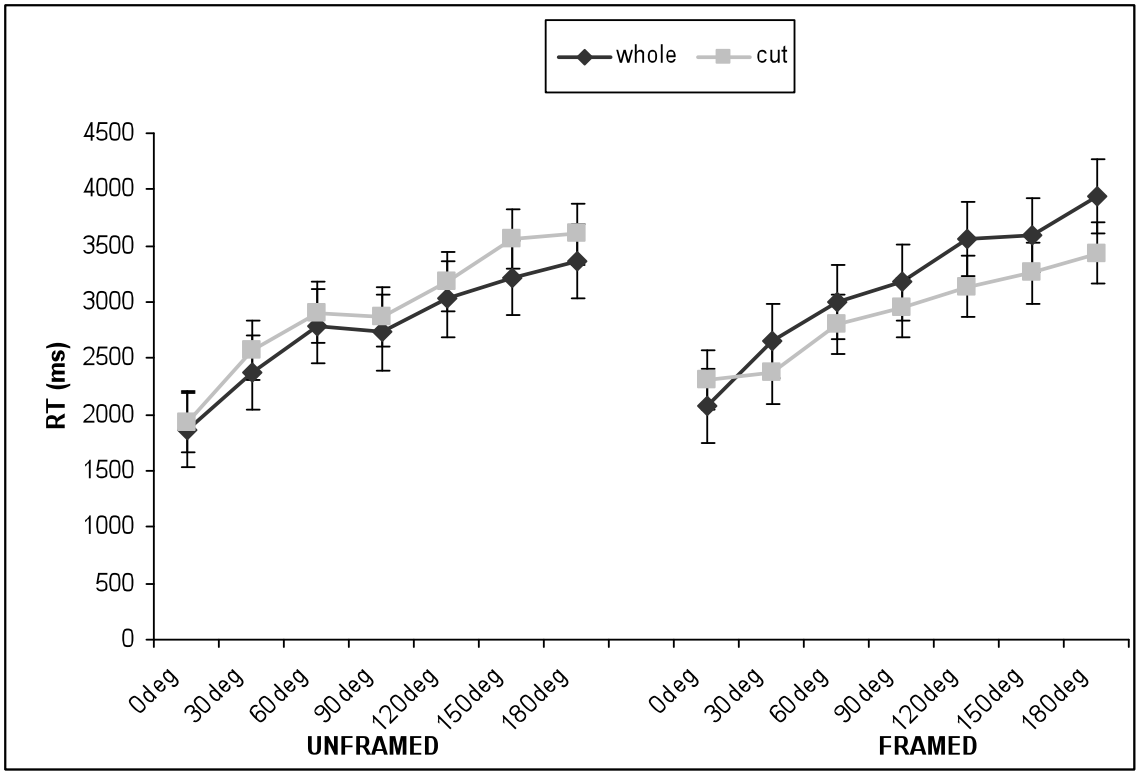


Figure 2-6. Unframed (left) and framed (right) RT data to whole and cut figures at each degree of rotation.

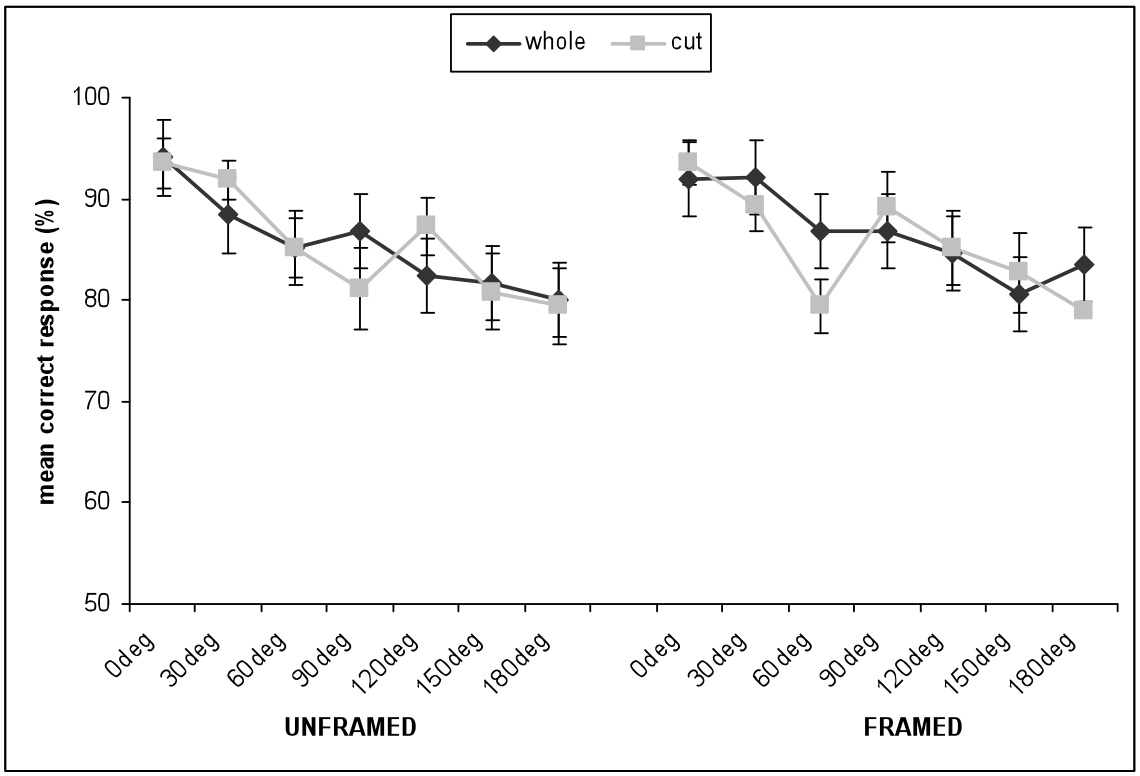


Figure 2-7 shows accurate whole and cut figure rotations for unframed (left) and framed (right) stimuli.

Individual Differences

Gender did not show a main effect. However, accuracy data showed a Gender and Angular Disparity interaction, F (6, 210) = 2.155, $p < .05$, MS_e= 177.507 (Figure 2-8). Female accuracy declined to a greater extent as a function of angular disparity, particularly greater than 60^0. No gender difference was found for RT data.

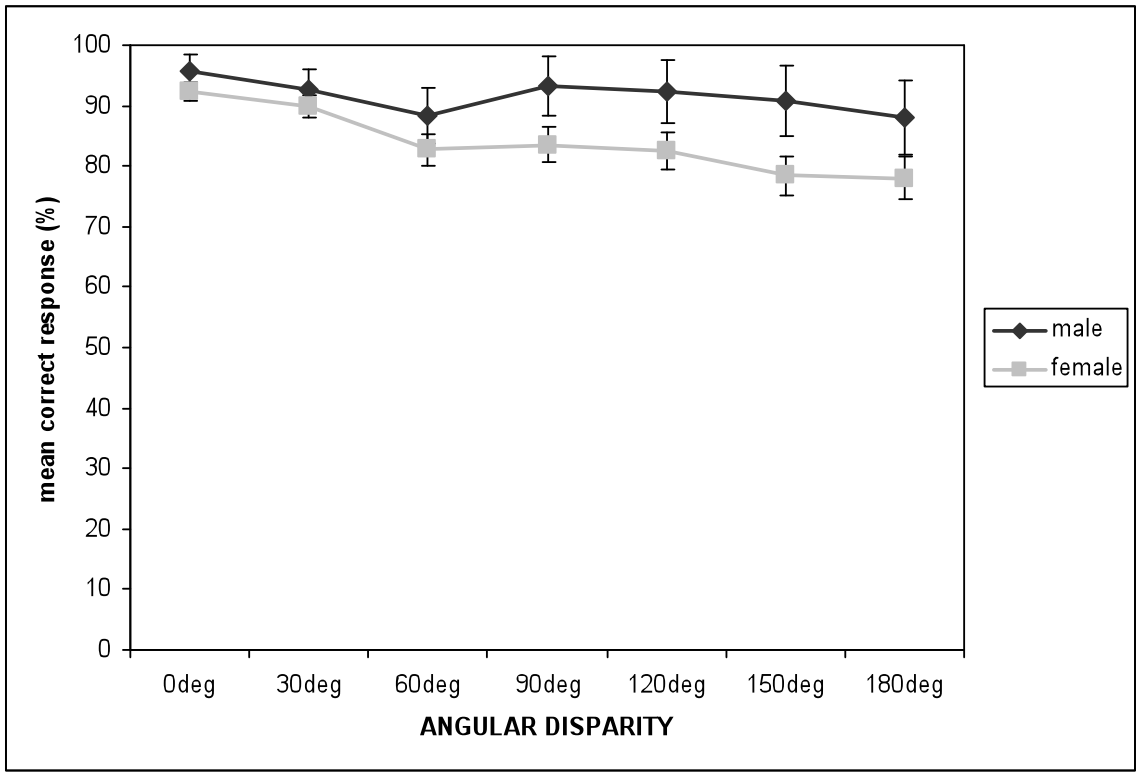


Figure 2-8 depicts males and females correct responses to figures as the degrees of rotation between the pairs increased.

Preference (map vs. verbal directions) did not show any main effects for RT or accuracy. However, Preference interacted with Frame for RT data, F (1, 32) = 6.412, $p < .05$, MS_e= 8048426.682. People who preferred maps responded faster to framed stimuli than those who preferred verbal directions, but there was no difference on unframed stimuli as a function of Preference (see Figure 2-9).

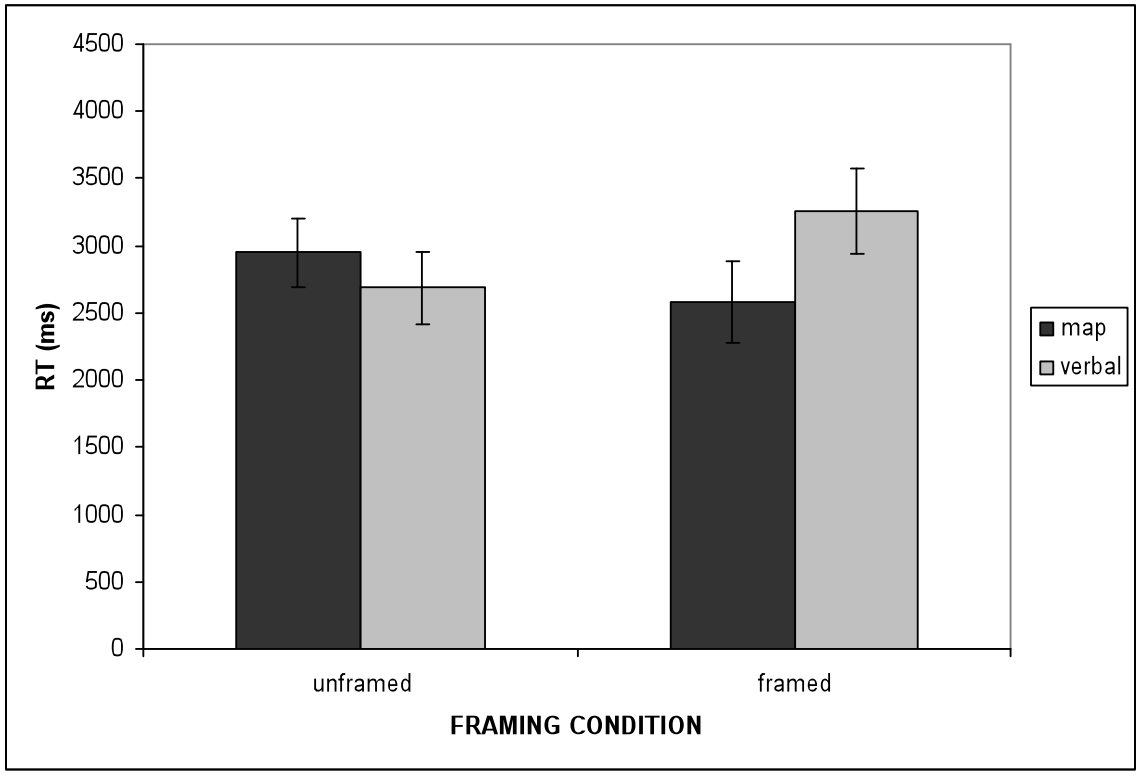


Figure 2-9. Response times to framed and unframed 2-D figure pairs as a function of Preference for spatial information learning.

Mental Representation did not show main effects or any interactions, other than the omnibus ANOVA results.

Discussion

Consistent with Experiment 1 findings, Experiment 2 showed an angular disparity effect (Shepard & Metzler, 1971). Also, the pattern that was shown to account for strategy differences in MR performance for gender was observed. The gap between male and female performance was more pronounced with greater angular disparities.

Participants performed on MR task differently when the stimuli were strategy consistent and had a frame around them. In other words, framing the figures affected "whole" figure rotation. When figures were framed, participants were faster with "whole" figures. This effect could further be observed as a function of angular disparity. Participants' rotation rates of "whole" and "cut" figures flipped with the existence of

frame. When there was no frame, they were faster to rotate “whole” figures than “cut” at each degree of rotation. However, with the frame, they rotated “cut” figures faster than “whole” ones. Moreover, framing pulled performance difference between “whole” and “cut” figure rotations together as a function of angular disparity. These could be explained in several ways; 1) Having a frame seemed to inhibit “whole” figure rotation, 2) Framing helped with the rotation of “cut” figures, or 3) Both. These ideas are discussed further in the next section.

Experiments 1 & 2: Interim Discussion

The hallmark finding of mental rotation shows response time increases and accuracy decreases as the angular difference between the figures increases (Shepard & Metzler, 1971). Experiments 1 and 2 showed an angular disparity effect, consistent with the literature (Blough & Slavin, 1987; Collins & Kimura, 1997; Cooper, 1975; Heil & Jansen-Osmann, 2008; Kail et al., 1979; Maccoby & Jacklin, 1974; Shepard & Metzler, 1971). Although we did not directly compare MR performance between Experiments 1 and 2, mental rotation of 2-D figures appears faster compared to rotation of 3-D figures, also consistent with the literature (Bauer & Jolicoeur, 1996; Collins & Kimura, 1997; Jordan et al., 2002).

Differences in slope of response functions of the MR task as a function of angular disparity suggested different strategies. Participants' rotation performance for "whole" and "cut" figures reflected the pattern that was suggested to account for holistic and piecemeal strategies, respectively. While holistic rotators are proposed to rotate figure as a whole, piecemeal strategy first divided the figure into pieces and rotated each piece one by one. Typical MR tasks use "whole" figures. However, we introduced "cut" figures to

promote piecemeal processing and further examine performance patterns as a function of strategy-consistent stimuli. Experiments 1 and 2 showed the *strategy difference pattern*, which is the more pronounced performance difference between groups with greater angular disparity. Participants performed even better with "whole" figures (or did worse with rotation of "cut" figures) with increasing angular disparity.

Individual differences measures showed similar findings as those with strategy-consistent stimuli. A number of studies in the MR literature show performance differences across genders that report men to perform better (Kail, et al., 1979; Linn & Petersen, 1985; Maccoby & Jacklin, 1974; Masters & Sanders, 1993; Richardson, 1994; Resnick, 1993; Voyer, Voyer, & Bryden, 1995). Males rotated even faster with greater angular disparities (Collins & Kimura, 1997; Kail et al., 1979) and while they were inferred to use holistic strategy, women were suggested to rely more on piecemeal strategy especially with more complex stimuli (Bethell-Fox & Shepard, 1988). Consistent with the literature, Experiment 1 found that males rotated 3-D figures faster than females (Collins & Kimura, 1997; Kail et al., 1979). We need to emphasize here that we did not merely examine gender effects, but other individual measures such as preference (map vs. verbal directions), and mental representation (survey- vs. landmark-centered) in spatial learning suggesting that if gender differences reflect distinct cognitive strategies, the way people represent spatial information should also reflect these strategies. As expected, we found *strategy difference pattern* that was shown with strategy-consistent stimuli (whole vs. cut figures) for gender, preference, and representation as well. MR performance of males, people who preferred maps, and ones who formed survey-centered representation suggested the use of holistic strategy by reflecting the "whole" figure response pattern.

However, people whose responses mimicked the cut figure pattern and the use of piecemeal-strategy, were females, landmark-centered people, and the ones who preferred verbal directions.

Another line of research supported possible differences in strategies through laterality in MR performance. Right hemisphere, overall, was involved in simple mental rotation task whereas left hemisphere was involved in more complex transformations (Milivojevic et al., 2003). For men, who were suggested to be holistic rotators, left hemisphere was activated during MR tasks (Jordan et al, 2002) whereas women's right hemisphere (Roberts & Bell, 2000) was activated and the same area was triggered by piecemeal strategy (Weiss et al., 2003).

Relations between individual and cognitive strategy differences helped us understand more about the underlying processes in mental rotation paradigm. Experiments 1 and 2 supported differential cognitive strategy use, if not already present, emerging with more complex stimuli. Dimensionality was used across experiments to account for complexity. Overall, we found that males were faster and more accurate with 3-D stimuli, consistent with the literature (Collins & Kimura, 1997; Linn & Petersen, 1985; Voyer et al., 1995). The difference did not hold for 2-D rotation and the performance gap between males and females closed, again consistent with the literature (Bauer & Jolicoeur, 1996; Collins & Kimura, 1997; Heil & Jansen-Osmann, 2008; Peters et al., 2005).

One of the possible explanations is that framing introduced a reference point or an additional spatial cue to the MR task. It interacted with strategy-consistent stimuli for both Experiments 1 and 2. However, the existence of frame affected "whole" figure

rotation differently for these experiments. For framed stimuli, Experiment 1 showed faster "whole" figure rotation at almost each degree of rotation getting even faster with greater angular disparity, In contrast, Experiment 2 showed faster "cut" figure rotation over degrees of rotation. Moreover, Experiment 1 "cut" figure rotation was much slower for "framed" stimuli, specifically by people who preferred verbal directions. Framing stimuli seemed to help people preferring maps, who supposedly used a more holistic strategy. In other words, framing seemed to help rotation of 3-D "whole" figures but hindered 3-D "cut" figures, and helped 2-D "cut" figures. This can be explained with previous research. Scenes, which are naturally 3-dimensional, when presented along with a frame were harder to process. Frame served as flatness cue (Eby & Braunstein, 1995) and decreased the perceived depth (Reinhardt-Rutland, 2003) possibly further confusing people to rotate especially “cut” figures. With 2-D stimuli, framing again provided additional information, but there was no clash in perception of dimensionality that all information was on the same dimension. Thus, frame we surrounded the figures with was drawn on a 2-D plane and forced people to think of the figure as 2-D. It is possible that with 3-D MR, framing added another dimension and increased cognitive load that it hindered the overall performance. However, with 2-D MR task, performance on piecemeal-consistent "cut" figures benefited from the existence of a frame.

In light of these findings, we suggest a mechanism for MR performance. Map use provides a whole, bird’s-eye view, which engages a more global representation. Global representation supports a more holistic strategy with whole figures. Since holistic strategy is reported to be more efficient on standard whole figures (Corballis, 1997) faster responses by males, who were suggested to use holistic strategy would be reasonable. Yet

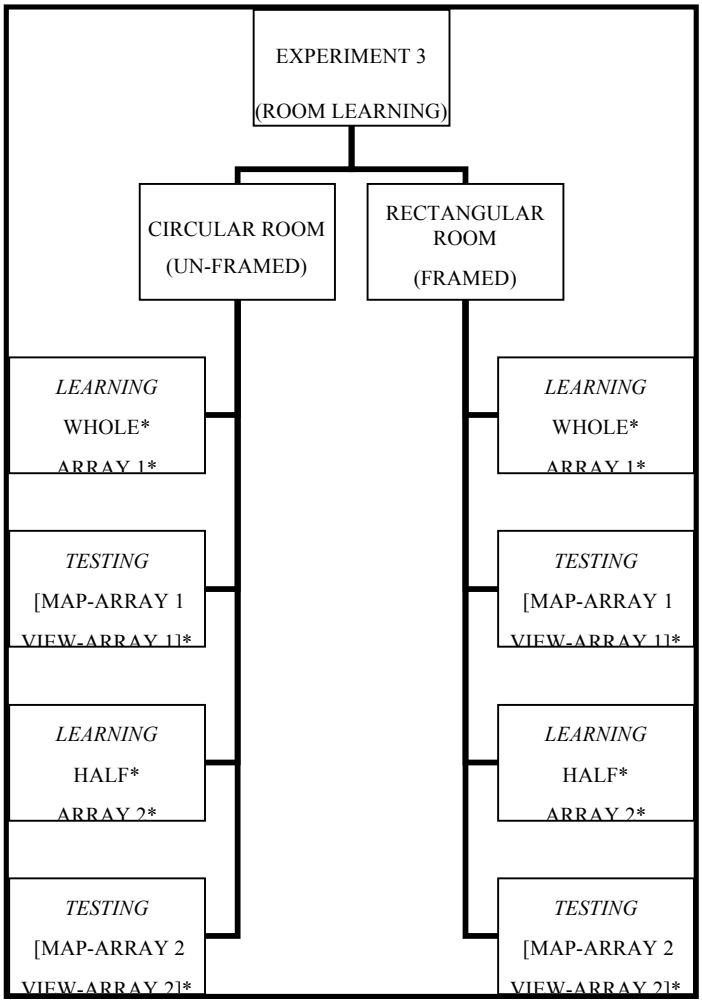
survey perspective and map preference, would also use holistic strategy and showed faster and more accurate responses with MR. However, verbal directions engage in serial information processing such as route or landmark perspective. Similarly, piecemeal strategy with cut figures for mental rotation also uses serial information processing. To our knowledge, the first two experiments are the first in the literature to examine rotation strategies as a function of whole and cut figures. We propose that the findings support how the use of strategies in MR clarifies the underlying processes by matching the performance of different individuals with strategy-consistent stimuli.

Experiment 3

Are mental rotation processes involved with memory for room-size arrays? How might strategies used in MR of objects be involved with learning and recalling objects within a room? The extent to which standard MR tasks and those involving perspective taking on spatial layouts draw on similar spatial abilities is investigated with Experiments 3 and 4.

Experiment 3 specifically examined memory for room-size layouts learned through direct experience. Participants learned an object array from two viewpoints and from one of two room structures (Experiment 3a: circular or Experiment 3b: rectangular). In addition to typical object-array studies (Mou et al., 2008b; Mou et al., 2009; Mou & McNamara, 2002; Shelton & McNamara, 1997; 2001), we used a room that could be divided in half, allowing learning of one half of the array at a time (see Figure 3-0). Learning in halves would engage piecemeal processing, similar to Experiments 1 and 2.

Testing involved two tasks requiring recognition of the presented at rotations different from the learned viewpoint. To this effect, two versions of an *array rotation* task were created. For both tasks, participants saw random three objects from the studied array and decided whether the objects were laid out the same way, yet possibly rotated, or as mirror reflection of what they learned. The two versions of the array rotation tasks differed only in the spatial perspective depicted; *map array rotation* presented map-like pictures of objects and *view array rotation* showed photographs taken from a viewpoint within the room (see Figure 3-1). The *map- array* promoted a survey perspective and the *view-array* task triggered a route perspective.



* denotes counterbalancing

Figure 3-1. Diagram of the procedure for Experiments 3 and 4. Experiment 4 would instead use maps.

Experiment 3a

Method

Participants

Thirty-three undergraduates from Tufts University participated for partial course credit or for pay. Of these people, 15 were females and 18 were males. None of them participated in the previous experiments.

Materials

Arrays. Two 9-object arrays were used. The layout formed a diamond configuration. Objects consisted of common household items identifiable from all viewpoints (see Figure 3-2). They were placed in the center of an approximately 8 feet (diameter) circular room.

Figure 3-2 shows example pictures of objects from both arrays. *Figure 3-2a* (two pictures on the left) depicts the presentation of objects in *map array task.* Two photographs on the right (Figure 3-2b) are examples to show how the view-array task was created. Note that Figure 3-2b has a tilted approach and includes curtains as if the viewer is studying within room.

Circular room. The experiment took place in two rooms. One room was for learning and the adjacent room was for testing. We created a circular chamber with PVC pipes and shower curtains in the learning room and hang within a standard room to make it circular. An additional curtain could divide the chamber in half when needed. There were five objects visible on each half keeping the center object to be seen from both

sides. This common center object (i.e., pan or towel) allowed participants to relate two halves of the layout.

Test Stimuli. The two memory tasks, *map array* and *view array* required different stimuli. Participants saw pictures of objects from the top for the *map array task* (see Figure 3-1), and photographs of each trial, taken from various viewpoints in the room, for the *view array task* (see Figure 3-2). The experimenter took photographs of objects with a Canon camera while standing up, as if studying the array.

Each trial for tasks included random three objects (triad) from a 9-object-array. There were 21 combinations of triads and each rotated on 30-degree increments for 0-180 degrees. With the rotations, there were 84 trials for each block and task (setting: whole-map task, whole-view task, half-map task, half- view task) totaling to 332 trials for the experiment. The only difference between the tasks was the nature of the stimuli. *Map-array* triads consisted of object pictures from above and *view-array* task instead included photographs of those objects. After creating "same" trials (Figure 3-3a and 3-4a), mirror reflections of the triads (Figure 3-3b and 3-4b) were created using Adobe Photoshop software. Objects could also be from the learned half (within) or from both halves of the array (between). One triad combination was used 4 times in one setting with different response (mirror or same) and source (from between halves or within-one-half). In other words, the number of same/ mirror and between-/within-one-half trials was the same (42 for each setting) and counterbalanced across conditions.

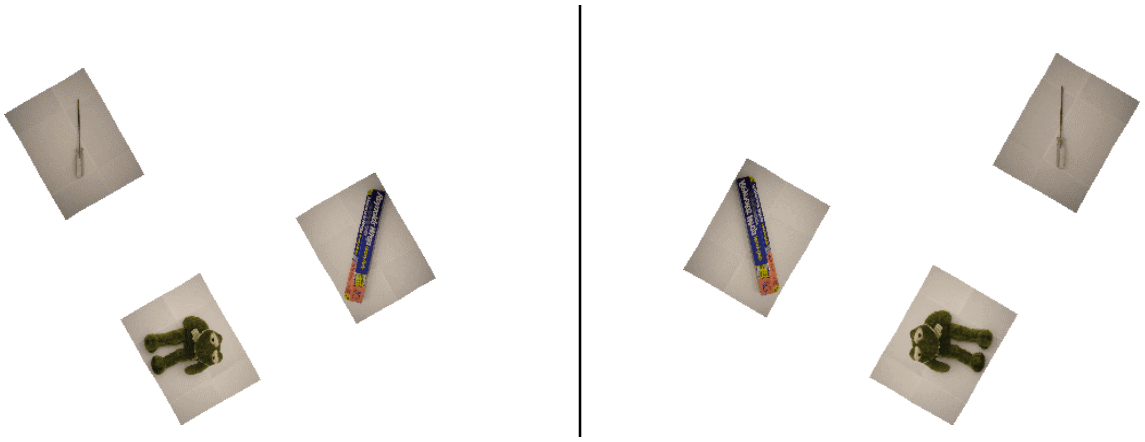


Figure 3-3a (left) is an example of a "same" triad with 60-degree rotation from the original array whereas *Figure 3-3b* (right) shows a mirror-reflection of this triad.

Figure 3-4a (*l*eft) shows an example of a "same" 120-degree rotation from the *view-array task* whereas *Figure 3-4b* (right) shows a mirror-reflection of this triad.

Other materials. Two questionnaires; individual differences and mental representation, and the stopwatch from previous experiments were used.

Procedure

Participants completed learning and testing phases for two different layouts, consecutively. They learned the first set of objects and completed testing related to this layout. They then studied the second array and did tasks related to the second one. While

one array was presented and learned as a whole, the other was presented with a curtain in the middle forcing the participant to study half of the room at a time. The order of the arrays and the way they were learned were counterbalanced.

After participants signed consent forms in the *testing room,* they were taken to the *learning room.* In the learning phase, the participant closed her eyes to be led into the circular room and positioned at a viewpoint defined as either 0-degree or 180-degree. Once in position, she opened her eyes to study the array for 30 seconds followed by a pointing session, where she closed her eyes and pointed to each object as the experimenter randomly named them. This studying-pointing cycle continued until the participant was able to successfully point to all objects in three pointing sessions which was the criterion for moving on to next step. Once reaching criterion from one viewpoint, the experimenter guided the participant, her eyes closed, to the other viewpoint (e.g., 180-degrees if she started with 0-degree). She repeated the same studying-pointing sessions from this new viewpoint. After reaching criterion on the second viewpoint, she was led to the testing room while her eyes were closed.

In the *testing phase* she sat in front of a monitor and read through the instructions. First, she read she would see three objects from a perspective within the room (view-task) or on a map (map-array task) reminding that the objects were from the layout she recently learned. She was required to respond as fast as possible, without sacrificing accuracy whether the objects had the "same" configuration or "mirror-reflection" of the way they were placed. She then saw example triads for “same” and "different" responses from the learned layout. She was notified to direct questions to the experimenter if anything seemed confusing. Once she read and understood the instructions, she initiated the

memory tasks. The procedure for the two memory tasks was identical, although the stimuli differed. For both, she first saw a fixation cross for 750 ms, and pressed a button to indicate that she was ready to see the actual trial. Unlike Experiments 1 and 2, the fixation cross remained on the screen for a fixed time period. For each trial, she decided triads to be "same" or "different" in relation to what was studied. She read the same set of instructions before each task, with the appropriate objects. After completing *map-array* and *view-array* tasks, she went through the two questionnaires as in previous experiments.

Trials were presented and data collected using Superlab software. The order of the presented arrays (1 or 2), learning blocks (whole or half), viewpoints (0- or 180-degrees), and tasks (map array or view array) were totally counterbalanced.

Experiment 3b

Because Experiment 3a used a circular room, participants could not rely on reference points (e.g., corner) for rotating objects in relation to one another. How might an additional reference frame affect representation of a room-size layout? Experiment 3b used a rectangular frame instead of the circular one. Previous studies have also examined learning an array of objects within circular and rectangular rooms (Kelly et al., 2008; Mou et al., 2007). Adding a frame around the figures seemed to help MR performance (Experiment 1) and drew a clearer distinction for strategies (Experiment 2). With this study, we examined the role of rotation in memory for room-size layouts through cognitive strategies and as a function of framing. Having a frame or a rectangular structure was expected to show an improved performance on overall rotation of larger-scale arrays.

Method

Participants

Thirty-seven Tufts University undergraduate students (21 females and 16 males) participated in this experiment. They received $10 compensation for their time. None of them took part in any of the previous experiments.

Materials

Rectangular room. This study used a rectangular chamber, also constructed with PVC pipes and shower curtains, instead of the circular one. Like Experiment 3a, a curtain could be used to divide the room and the array in half.

Stimuli. The photographs that were used in *view array* task of Experiment 3a included parts of the curtain (see Figure 3-4). Thus, for some triads circular room structure could be observed. Those photographs were taken again as to capture the rectangular structure of the room and were replaced. *Map array* stimuli as well as other materials were identical to those of Experiment 3a. The other materials were also the same as in Experiment 3a.

Procedure

The procedure was identical to that of Experiment 3a.

Results

Coding and Analysis

Dependent measures included reaction time (RT) and accuracy. Consistent with the previous experiments, data trimming involved eliminating each participant's highest and lowest RT at each degree of rotation (Bush et al., 1993). Six participants did not

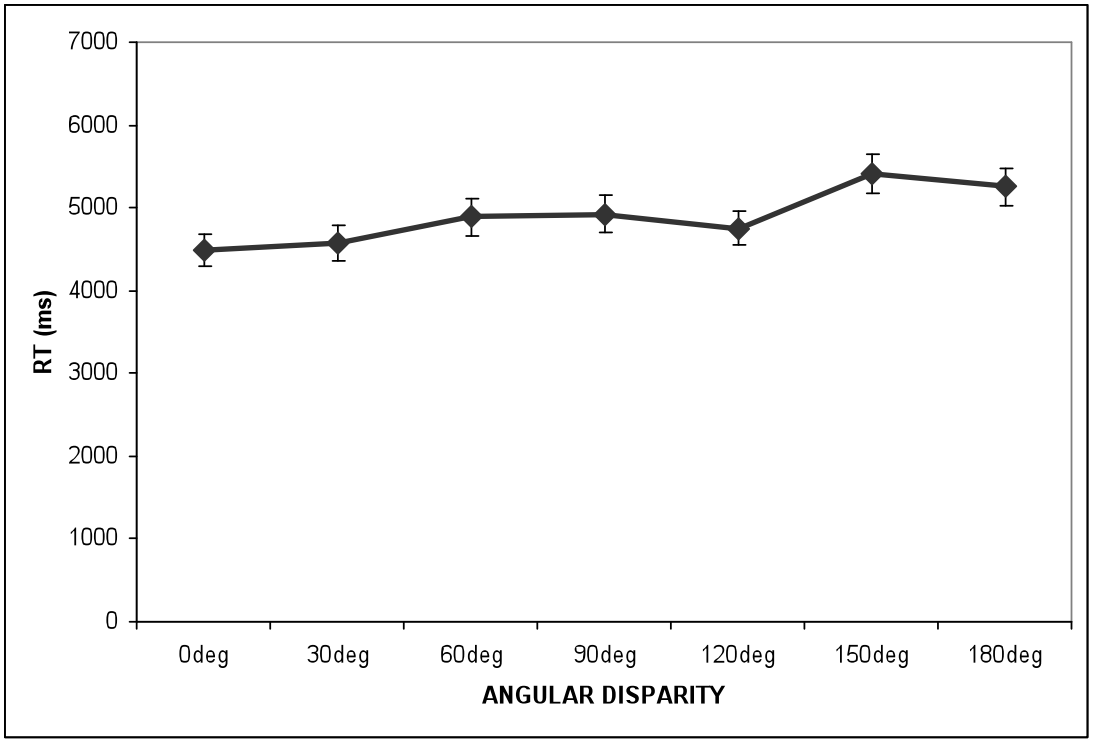
properly follow the instructions, thus their data were eliminated from the analyses. Ratio of correct responses was computed for each participant.

Angular Disparity (0, 30, 60, 90, 120, 150, and 180), and Array Accessibility (whole, half) were within-participant factors. Between-participant factors of primary interest included Room Geometry and the individual difference measures including Gender (male, female), Preference (map, verbal), and Representation (survey, landmark).

Repeated-measures analysis of variance (ANOVA) on accuracy and RT data was conducted first with a 2 (Figure Consistency) X 7 (Angular Disparity) X 2 (Room Geometry) mixed-factorial design. Individual difference measures were separately entered into the analysis as 2 (Gender), or 2 (Preference), or 2 (Representation). We reported the results of the omnibus ANOVA followed by additional results evident with each individual difference factors. The results were also reported consecutively for the view-array task and the map-array tasks.

View-array task

Angular Disparity. Results showed angular disparity main effect for both RT and accuracy; F (6, 372) = 14.099, $p < .001$, MS_e= 1033065.72 and F (6, 372) = 8.952, $p < .001$, MS_e= 77.92, respectively. As angular disparity between the array and the trials increased, RT generally increased (Figure 3-5a) while accuracy generally decreased (Figure 3-5b). We did simple and repeated contrasts and found that 0^0 was significantly faster in comparison to other degrees. Differences were also reliable for 30^0 vs. 60^0, and 120^0 vs. 150^0. Simple contrasts for accuracy data also showed that 0^0 was more accurate than the other angular disparities. Accuracy between 150^0 vs. 180^0 was also significant.



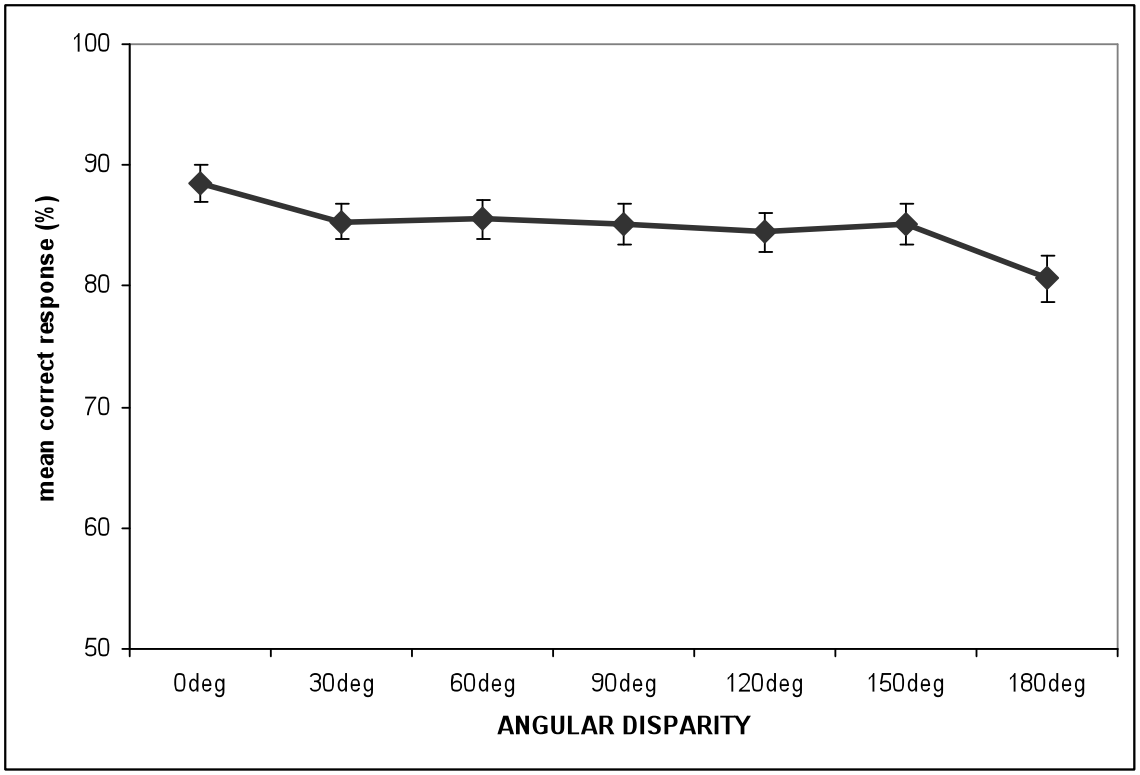


Figure 3-5a (top) shows the rate of rotation whereas *Figure 3-5b (bottom)* displays the correct percentage of rotation.

Array Accessibility assessed general spatial integration by comparing learning the array as a whole or one half at a time. This variable did not show a main effect. However, for accuracy data, it interacted with Angular Disparity, F (6, 372) = 2.679, $p < .05$, MS_e= 73.56. Whole- and half-array patterns did not vary systematically as a function of angular disparity (see Figure 3-6).

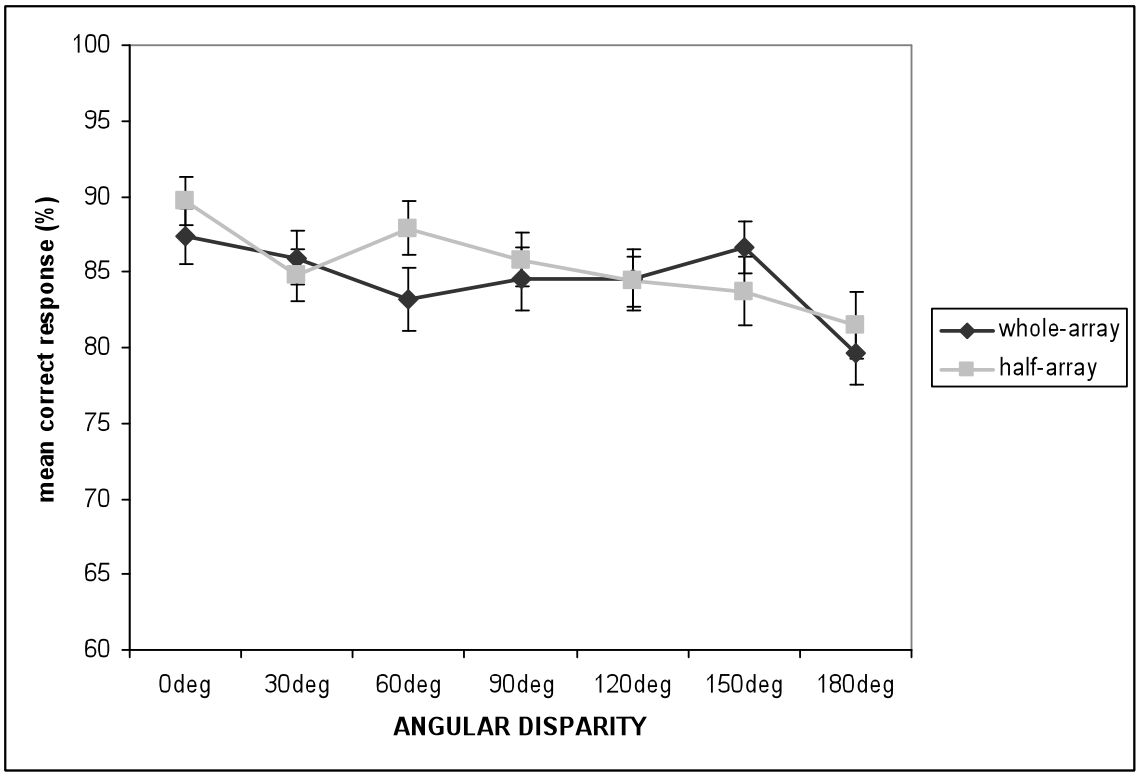


Figure 3-6. The accuracy rate for rotation of whole- and half-arrays from memory as a function of angular disparity.

Room Geometry did not show a main effect. However, the accuracy data showed a Room Geometry X Angular Disparity interaction, F (6, 372) = 2.945, $p < .01$, MS_e= 77.92. Rectangular room showed higher accuracy at 0^0 (one of the learned viewpoints) and approximately the same accuracy for the other angles. Whereas people showed approximately the same accuracy at other degrees for circular room except had lowest accuracy at 180^0 (the other learned viewpoint) (see Figure 3-7).

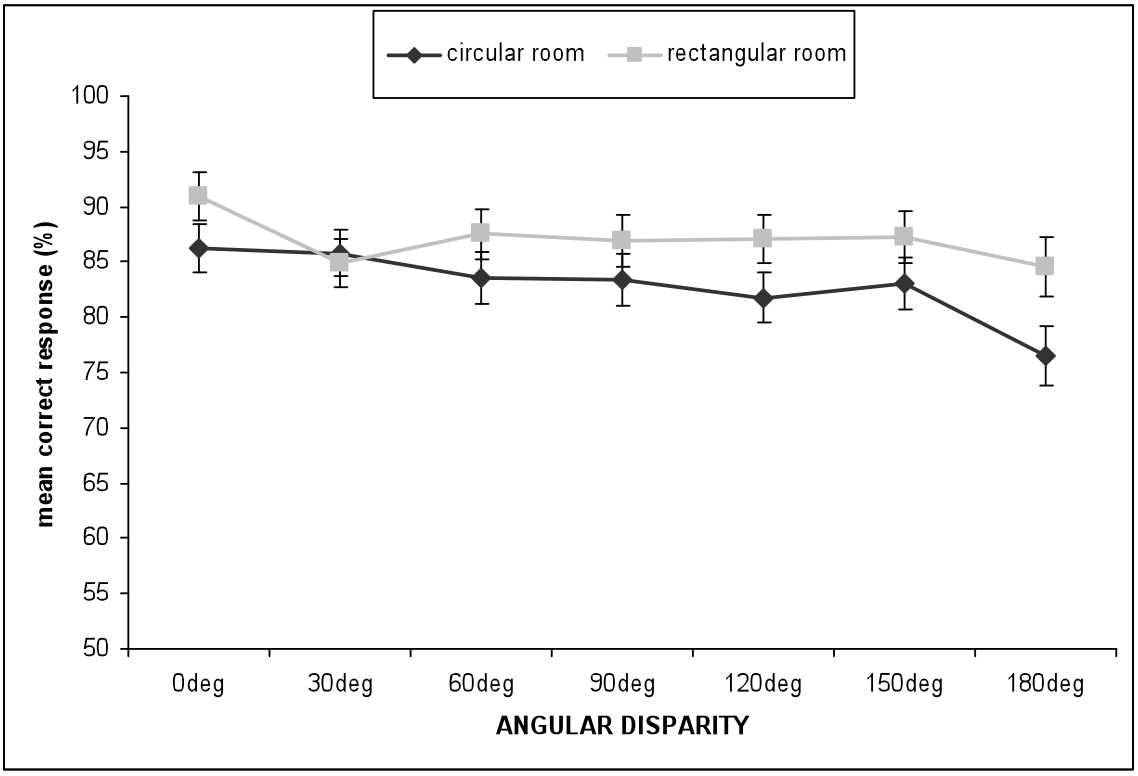


Figure 3-7 depicts how accuracy of framed or unframed layouts changed as degrees of rotation between the pairs increased.

Individual Differences

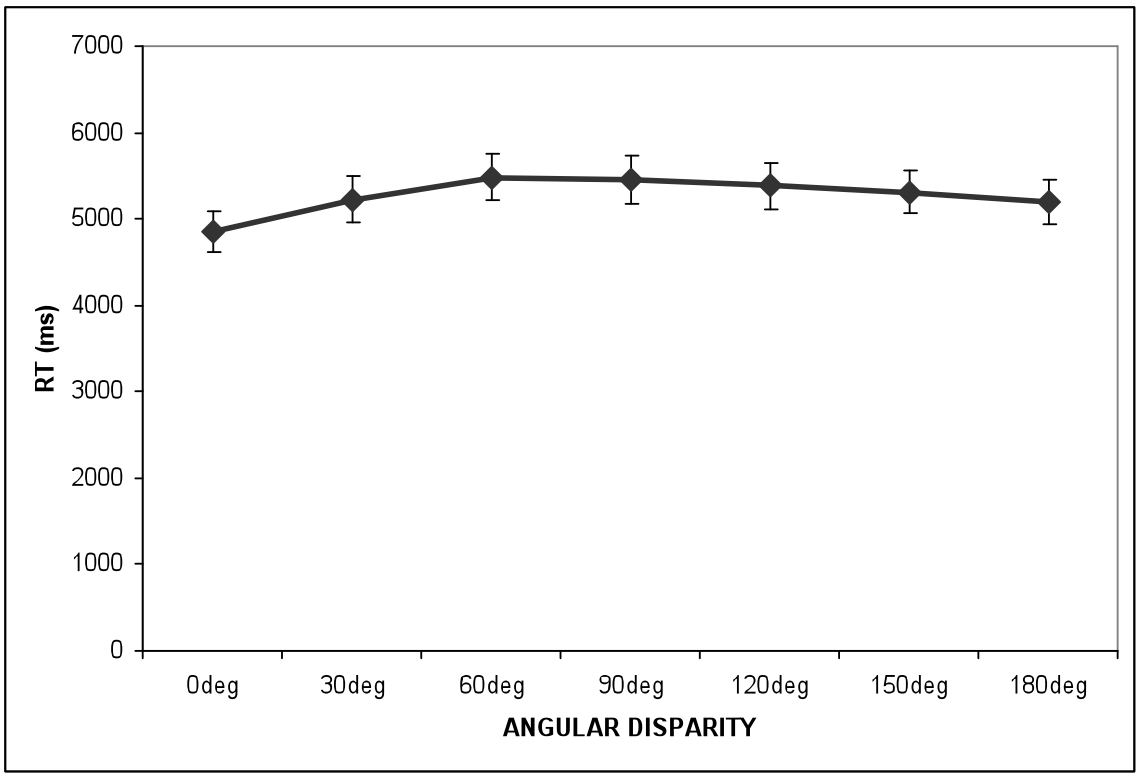
Gender and Mental Representation did not show main effects or interactions for either of the dependent measures, beyond the previously reported results.

Preference. Accuracy data showed a main effect of Preference; F (1, 59) = 10.767, $p <$ .01, MSe = 246.033, where participants who preferred maps (M= 88.49 %) were more accurate than those who preferred verbal descriptions (M= 78.84 %). No other interactions were found.

Map-array task

Angular Disparity showed main effects with both RT, F (6, 372) = 3.717, $p < .001$, MS_e = 1536194.249, and accuracy data, F (6, 372) = 3.114, $p < .01$, MS_e = 123.987. Specifically, participants responded slower as degrees of rotation between the array and

the presented trials increased up to 60^0, but for greater degrees of rotation responses were more rapid (Figure 3-8a). Responses to 180^0 showed declined reduced accuracy (see Figure 3-8b). We did simple contrasts and found that 0^0 was significantly faster than the other degrees of rotation, and 180^0 was significantly different than 0^0 and 60^0. For accuracy data, 0^0 was more accurate than only 180^0 and 180^0 was significantly slower than 0, 30, 90, 120 and 150 degrees of rotation.



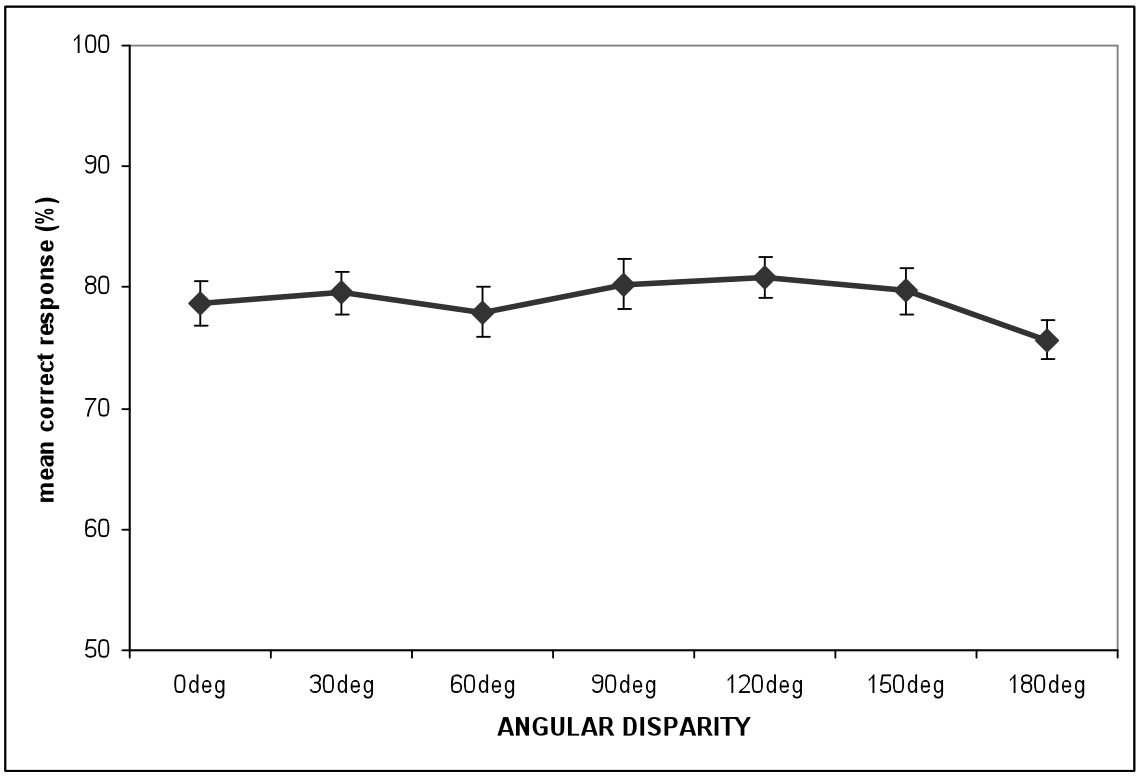


Figure 3-8 presents rotation rate (3-8a; top) and accuracy (3-8b; bottom) as a function of angular disparity.

Room Geometry did not show an overall effect. However, RT data showed a three-way interaction between Room Geometry X Array Accessibility X Angular Disparity, F (6, 372) = 2.67, $p < .05$, MS_e= 1057682.407.

Response patterns from memory after learning whole- and half arrays were reversely similar to one another (see Figure 3-9). Response pattern after whole-array learning within a circular room (Figure 3-9; left, dark line) showed consistency with the response of half-array learning within a rectangular room (Figure 3-9; right, light line). Participants were faster for 0^0 and 180^0 viewpoints, slowing down towards the middle. Consistently, half-array learning pattern in a circular room (Figure 3-9; left, light line) looked like that of whole-array in a rectangular room (Figure 3-9; right, dark line) showing a rather U shape.

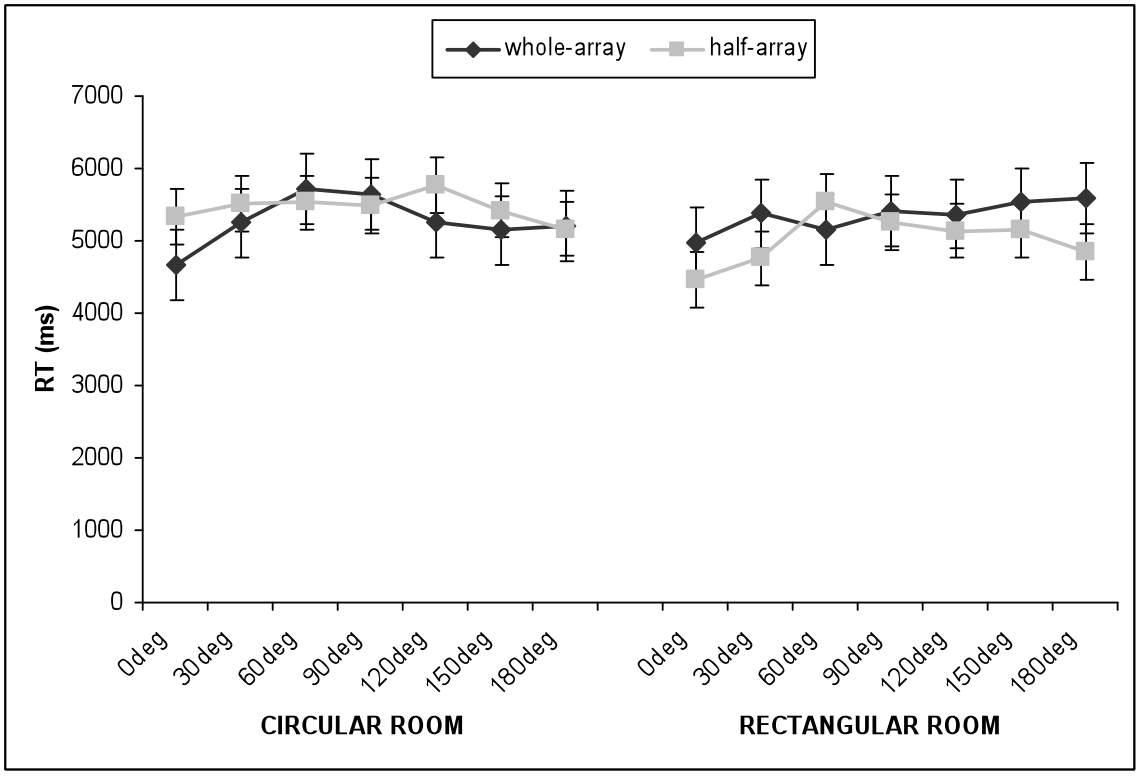


Figure 3-9 shows mental rotation response times after whole and half array learning within circular (left) and rectangular room (right) as a function of angular disparity.

Individual Differences

Gender did not show a main effect for the map-array task, nor did it interact with any of the other factors.

Preference. Preference showed a main effect for the Accuracy data, F (1, 59) = 6.216, p < .05, MS_e= 2172.8. Participants preferring maps (M= 82.02 %) over verbal directions (M= 73.79 %) were more accurate.

A four-way interaction of Angular Disparity X Array Accessibility X Frame X Preference, F (6, 354) = 2.269, p < .05, MS_e= 1058840.74 was found with RT data. This interaction was hard to interpret.

Mental Representation showed a main effect with accuracy data, F (1, 60) = 4.299, $p <$ .05, MS_e= 2216.03. Survey-centered participants were more accurate (M= 82.66 %) than landmark-centered ones (M= 76.09 %).

Discussion

An angular disparity effect, consistent with the MR literature (Blough & Slavin, 1987; Collins & Kimura, 1997; Cooper, 1975; Heil & Jansen-Osmann, 2008; Kail et al., 1979; Maccoby & Jacklin, 1974; Shepard & Metzler, 1971), was partially evident with Experiment 3 results. The angular disparity pattern was different for view- and map-array tasks. Participants learned the room-size object array from two viewpoints; 0^0, where they were standing when entered the room, and 180^0, where they learned from the opposite side of the array. View-task showed a rather linear increase as angular disparity increased. However, map-array task showed a pattern more similar to viewpoint-dependency (Shelton & McNamara, 1997, 2002) with more rapid rotation rates at learned viewpoints (0^0 and 180^0).

Room geometry affected the overall response patterns. Framing, used in the previous experiments, was operationalized through the geometry of the room. The walls and corners of the room created a rectangular structure that served as a frame while the circular room did not have these references available. Rectangular room seemed to help the performance of rotation from memory, more so with increasing disparity.

Having a reference frame and learning whole array of objects at once might have increased cognitive load to a degree that it hurt performance. For a circular room, whole-array learning showed better representation and for a rectangular room, learning half-array showed better representations. This was expected, because lack of a reference point

or an environmental cue forced global representation style and whole-array was used to promote a more holistic strategy. Rectangular room, however, where a reference frame is present, hindered performance after learning whole-array and helped with half-array learning. Frame around the array provided additional spatial information and learning information from half of the array seemed to be enough for spatial capacity. This also suggests that learning the whole-array from memory was more demanding with rectangular maps.

The pattern consistent with strategy differences was found for individual difference measures in previous experiments. We did not specifically replicate these findings, but people who preferred maps were overall more accurate than those who preferred verbal directions. And they formed better representations if these were more likely to be survey-centered than landmark-centered. Consistent with the explanation above, people who prefer maps and those who are more inclined to have survey-like representations were suggested to form a more global representation of the learned environment and global representation style was suggested to fit better with more holistic processing.

Experiment 4

Experiment 4a

Learning through navigation or direct experience might lead to different mental representations than learning from maps (Bilge & Taylor, submitted; Thorndyke & Hayes-Roth, 1987). These learning modalities, first of all, engage different psychomotor activities and use different perspectives; navigation uses route and maps use survey reference frames. Moreover, maps present layouts in 2 dimensions whereas directly

experiencing an environment (i.e., set of objects in a room) presents 3-D input. Therefore, the following experiments investigated the effect of map learning on mental rotation of room-size arrays and examined whether representation of layouts would differ as a function of learning source, which would be indicated by differential performance on array rotation.

Method

Participants

Seventeen female and 16 male undergraduates from Tufts University took part in this experiment. They received $10 for their participation. None of them participated in previous experiments.

Materials

Maps. Two sets of objects, same as in Experiment 3, formed two arrays. As in Experiment 3, each array formed a 9-object-diamond configuration. Two circular maps were created with Adobe Photoshop for each array. After creating the diamond shape with the array, a dotted circular frame was inserted onto the map and printed out map was cut from the dotted lines leading to a circular map. Blank white paper covering only half of the map was prepared to enable half version of the maps. Identical to Experiment 3, the center object was kept constant in presentation of both halves. Two arrays were printed out onto two sheets of transparencies for coding.

Objects in each array and the stimuli for each task (*map array* and *view array*) were identical to Experiment 3a. Two questionnaires were used again.

Procedure

Participants completed learning and testing phases, similar to Experiment 3a. However, learning phase was modified as to learn arrays from maps instead of objects on the floor as in Experiment 3 (see Figure 3-0). In the *learning room* participants were seated in the center of the room and were presented with either a whole or half map of one of the arrays. After studying the map for 30 seconds, they redrew the map for study cycle of the learning phase. To meet the criterion and continue with testing, they were required to relocate the objects in relation to one another three times in succession. Experimenter placed a map-printed-transparency underneath the participants' drawing. If the locations of objects matched with the transparency, it was coded as a successful trial. After criterion learning was established from two viewings of the map; 0-degree and 0-degree viewpoints, participants were taken to the *testing room* and completed *map-array* and *view array tasks,* in counterbalanced order. Learning and *testing stages* of the second array was followed by administering two questionnaires.

Experiment 4b

Method

Participants

Thirty-four Tufts undergraduates (19 females and 15 males) participated in this experiment in exchange for $10. None of them were in any of the previous experiments.

Materials

The only modification in this experiment is the frame shape around the arrays. The maps were presented in a rectangular shape. The rest of the materials were the same as Experiments 3b.

Procedure

The procedure followed Experiment 4a identically, with the modification of map shape. Thus participants received two rectangular maps, *whole* and *half* in counterbalanced order.

Results

Coding and Analysis

Dependent measures included *accuracy* and response time (RT). Consistent with the previous experiments, we trimmed each participant's highest and lowest RT at each degree of rotation (Bush et al., 1993). Three people's data were eliminated because they failed to follow the instructions.

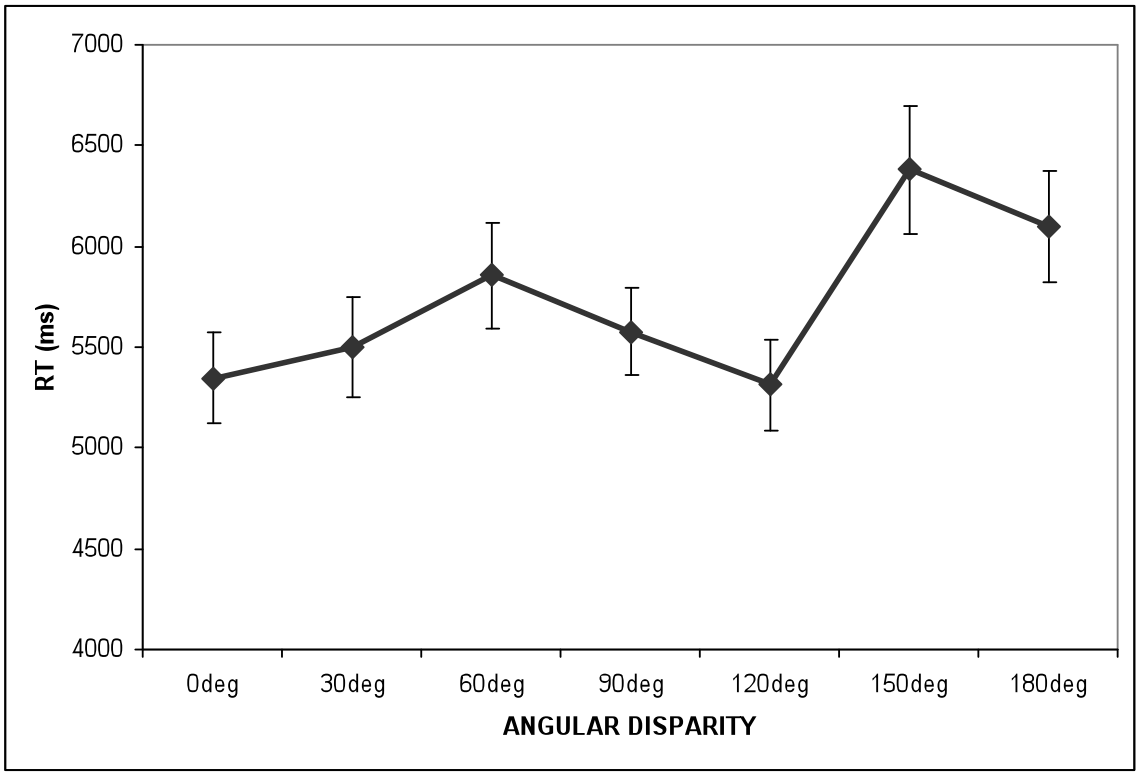
Angular Disparity (0, 30, 60, 90, 120, 150, and 180), and Array Accessibility (whole, half) were within-participant factors. Between-participant factors included Map Geometry (circular, rectangular) and the individual difference measures: Gender (male, female), Preference (map, verbal), and Mental Representation (survey, landmark). Individual difference measures were analyzed separately.

Analyses consisted of ANOVAs on RT and accuracy data using a 2 (whole, half) X 7 (degrees of rotation) X 2 (circular, rectangular) mixed-factorial design. Individual difference measures were then included in this ANOVA, one by one. We reported the results of the omnibus ANOVA followed by additional results with each individual difference measure. Similar to Experiment 3, we reported results of view-array and map-array tasks consecutively.

View-array task

Angular Disparity showed main effects both with RT, F (6, 372) = 11.477, MS_e= 1816074.082, and accuracy data, F (6, 372) = 4.483, MS_e= 112.834. As angular disparity

increased, participants responded unsystematically with rate of rotation (see Figure 4-1a) but less accurately (Figure 4-1b). Simple contrasts showed that participants were significantly faster at 0^0 in comparison to 60^0, 150^0, and 180^0. They were also significantly slower at 180^0 than at 30^0, 90^0, and 120^0. Simple contrasts for accuracy data showed participants to be more accurate at 0^0 than all the other degrees except 90^0 while at 180^0 they were less accurate than 0^0 and 90^0.



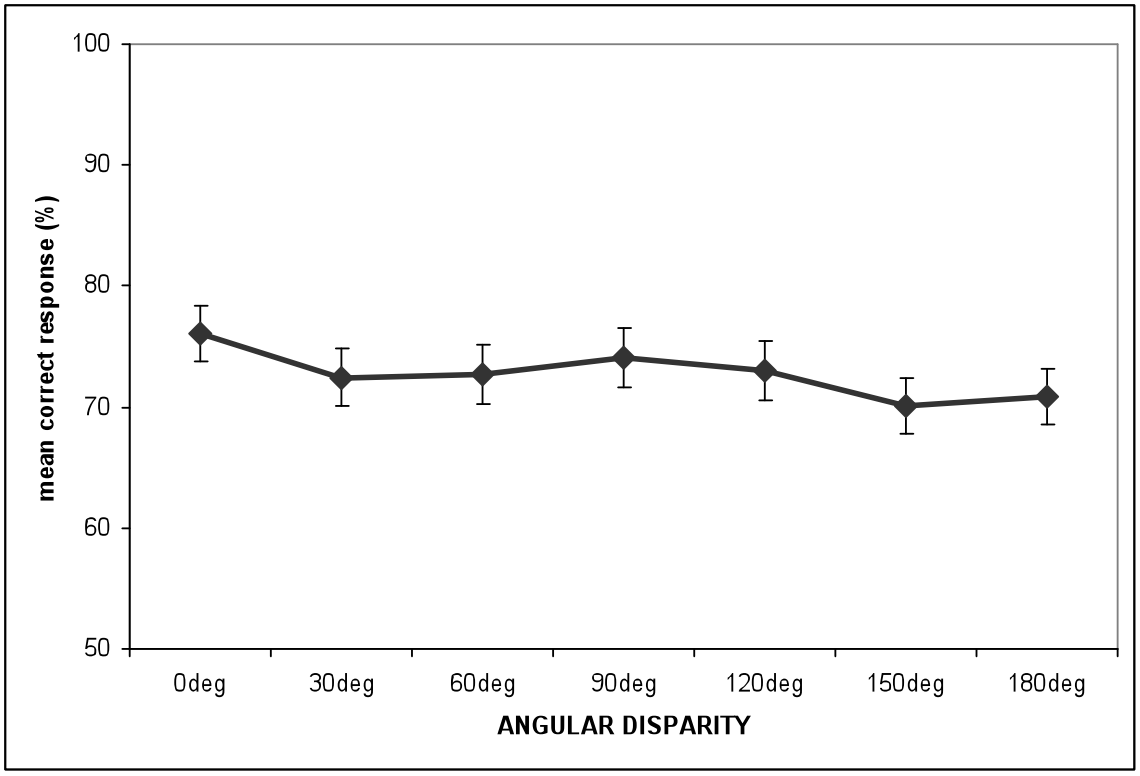


Figure 4-1 shows mean RT (Figure 4-1a; top) and accuracy (Figure 4-1b; bottom) at each degree of rotation.

Array Accessibility showed a main effect with accuracy data, F (1, 62) = 4.777, $p < .05$, MS_e= 806.697. Learning half-array at a time (M= 74.81 %) generated more accurate responses than learning whole-array at once (M= 70.67 %). Array Accessibility also interacted with Angular Disparity with RT data, F (6, 372) = 2.236, $p < .05$, MS_e= 1759915.585. Overall, performance after half-array learning was faster than whole-array learning (except at 0^0 viewpoint) and this difference was more pronounced with larger degrees of rotation (i.e., 150^0 and 180^0) (see Figure 4-2).

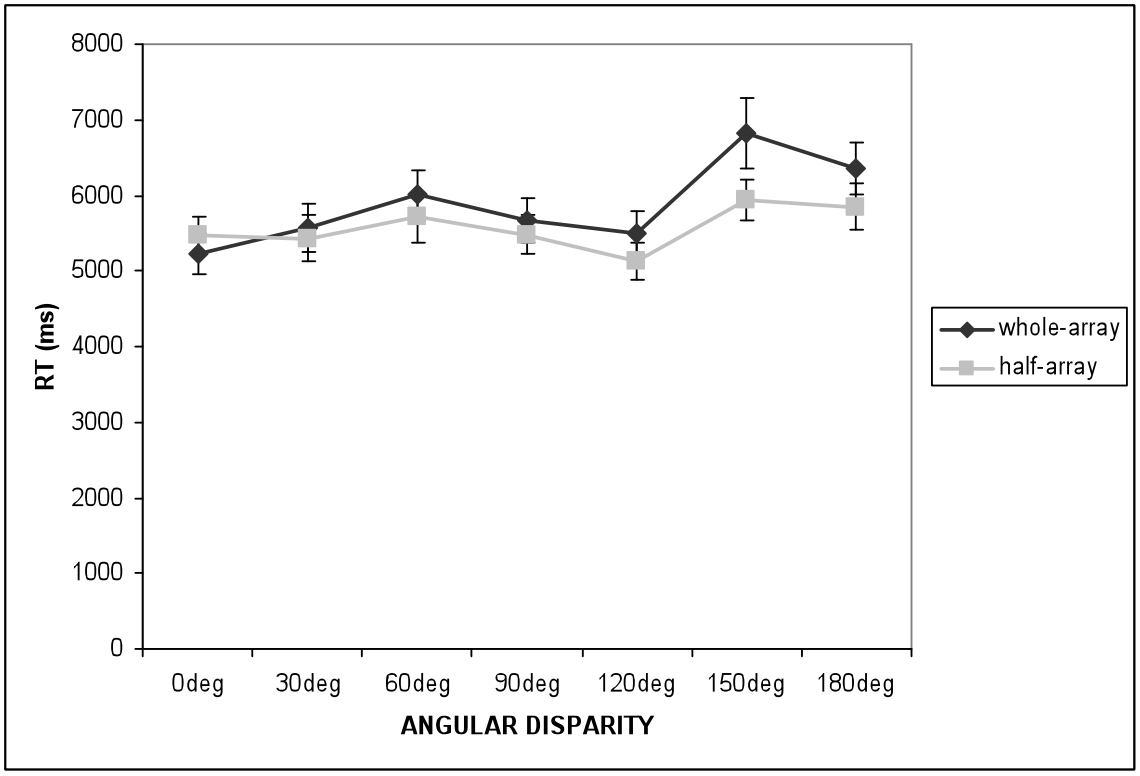


Figure 4-2. Mean rotation rates of whole- and half-arrays from memory at each degree of rotation.

Map Geometry did not show main effect with either of the measures. However, RT data showed an interaction between Map Geometry X Angular Disparity, F (6, 372) = 3.502, $p < .01$, MS_e= 1816074.082. Overall, participants responded faster after studying the circular map and showed a rather flat effect with the circular map whereas with the rectangular map, their responses were more unsystematic (see Figure 4-3).

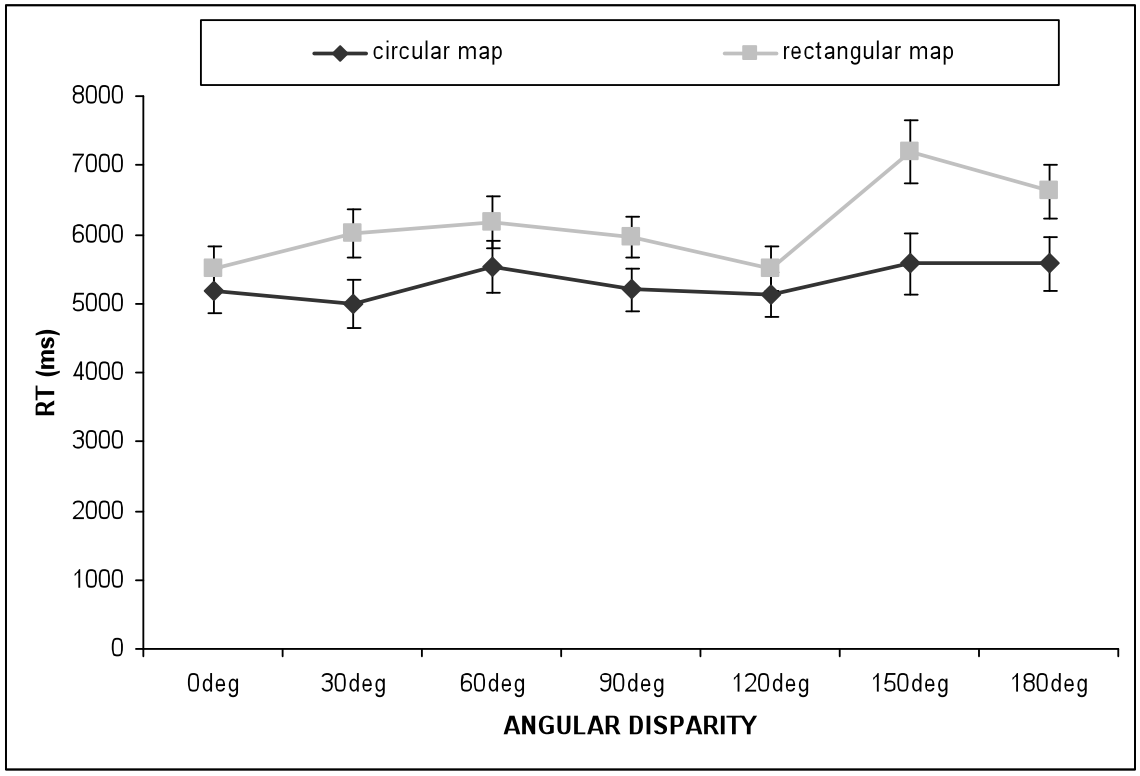


Figure 4-3. Rotation rate for circular and rectangular maps as a function of angular disparity.

The RT data also showed a three-way interaction between Map Geometry X Angular Disparity X Array Accessibility, F (6, 372) = 2.851, p = .01, MS_e= 1759915.59. With the circular map, participants responded similarly whether they learned with the whole- or with each half separately whereas in the rectangular map, they responded faster after half-array learning and this difference was more pronounced at greater angular disparity (see Figure 4-4).

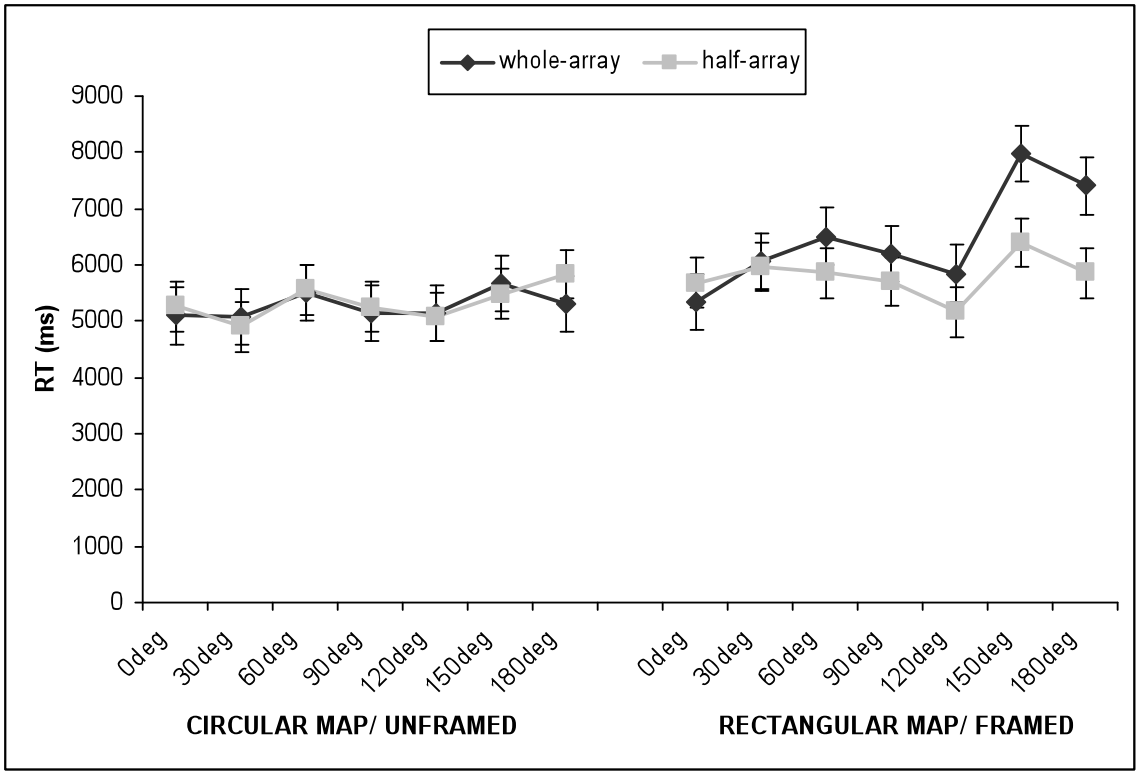


Figure 4-4. Mean RT to whole- and half-learned arrays as a function of angular disparity from circular (left section) and rectangular (right section) maps.

Individual Differences

Gender did not show main effect or any interactions other than omnibus ANOVA results.

Preference did not show an effect itself. However, it pulled new effects for Map Geometry. With the inclusion of Preference in the omnibus ANOVA, Map Geometry showed a main effect with accuracy data, F (1, 60) = 4.622, $p < .05$, MS_e= 4245.22. Participants were more accurate after learning with rectangular map (78.97 %) than circular map (68.55 %).

Mental Representation did not show a main effect. However, RT data showed a three-way interaction between Representation X Angular Disparity X Array Accessibility, F (6, 360) =2.114, p = .05, MS_e=1738960.06. Survey-centered people responded slightly faster to learning whole-array at 0^0 while landmark centered people were faster at 180^0 after

learning half-arrays. Moreover, people who had survey-centered representations showed a similar response pattern after whole-array learning (Figure 4-5a; dark line) as that of landmark-centered people after learning whole-array (Figure 4-5b; dark line). However, response patterns of survey-centered people after learning half-arrays (Figure 4-5a; light line) differed from that of landmark-centered people after half-array learning (Figure 4-5b; light line) that survey-centered people were faster at 0^0 and slowed down at 180^0 whereas landmark-centered people were as fast at 0^0 and 180^0.

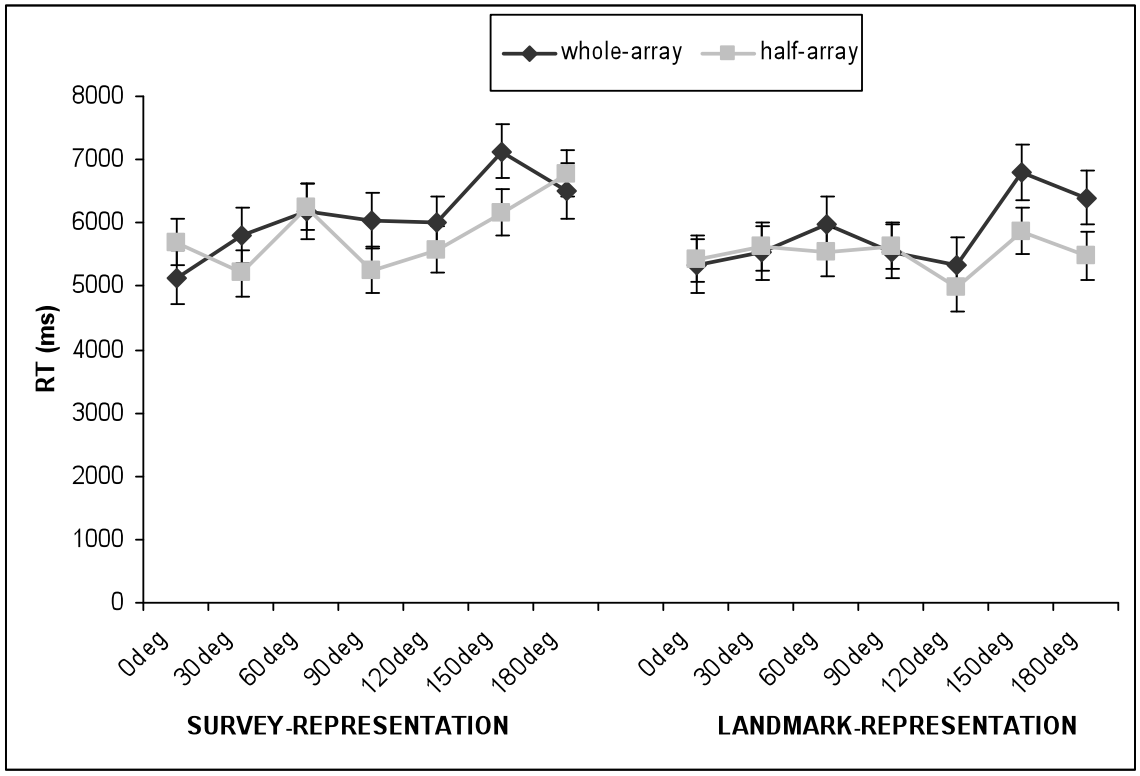
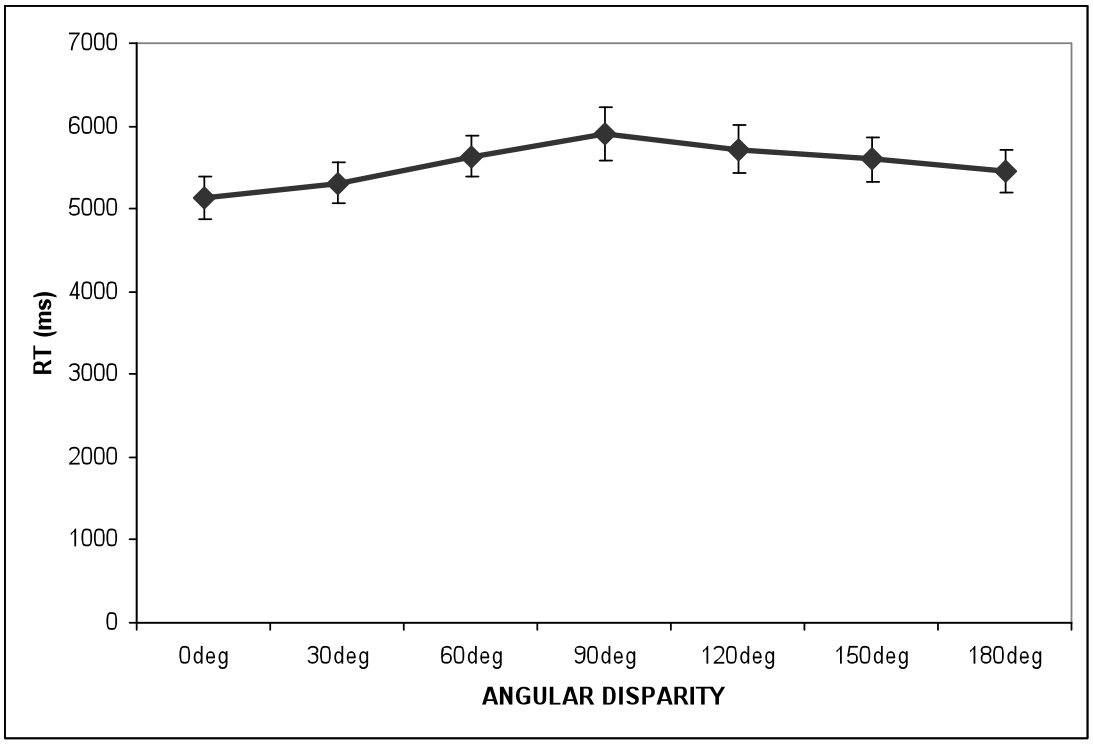


Figure 4-5. Survey- (4-5a) and landmark-centered (4-5b) people's performance after whole- and half- array learning over degrees of rotation.

Map-array task

Both RT and accuracy differed as a function of Angular Disparity, F (6, 372) = 5.048, $p < .01$, MS_e= 1699858.51, and F (6, 360) = 3.783, p = .001, MS_e= 108.64, respectively (Figures 4-6a and 4-6b). Participants responded faster at 0^0 and 180^0 viewpoints, slowing

towards 90^0 from both ways. Accuracy data however, showed decline for degrees greater than 120^0. Simple contrasts showed similar results, participants were faster at 0^0 than all other rotations except 30^0 and they responded significantly different at 180^0 in comparison to 90^0. For accuracy data, people different significantly between 0^0 vs. 120^0. And they were different at 180^0 in comparison to 60^0, 90^0, 120^0, and 150^0.



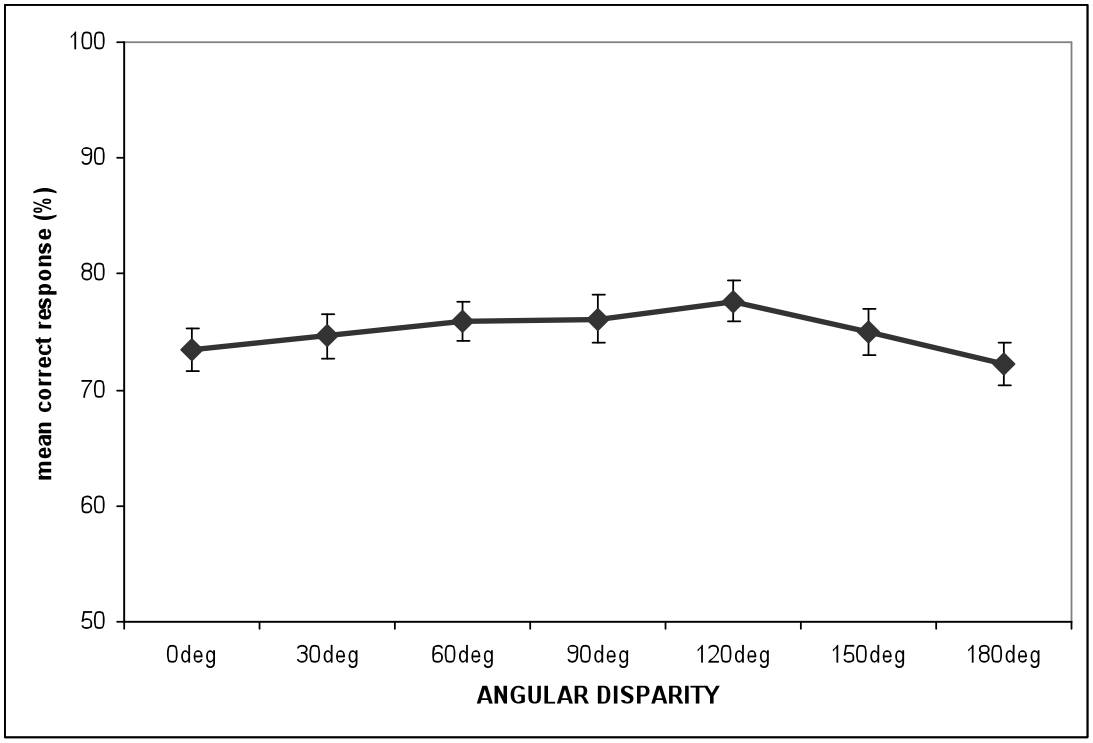


Figure 4-6. Rotation rate (4-6a; top) and accuracy (4-6b; bottom) as rotation between the trial and the original layout increases.

Spatial Integration. Learning the maps as a whole or one half at a time did not show any effect with either RT or accuracy data.

Map Geometry showed a main effect with accuracy, F (1, 60) = 10.378, $p < .01$, MS_e= 2499.54. Participants responded more accurately with rectangular maps (M= 80.38 %) than circular maps (M= 69.62 %).

Individual Differences

Adding Gender variable into analysis did not show any additional effects other than the ones reported with omnibus ANOVA.

Preference. There was no main effect for Preference. Analyses showed a marginal interaction of Preference X Map Geometry with accuracy, F (1, 60) = 3.835, p = .055, MS_e= 2411.25. People who preferred verbal directions responded more accurately for

rectangular maps. However, for circular maps those who preferred maps were more accurate (Figure 4-7).

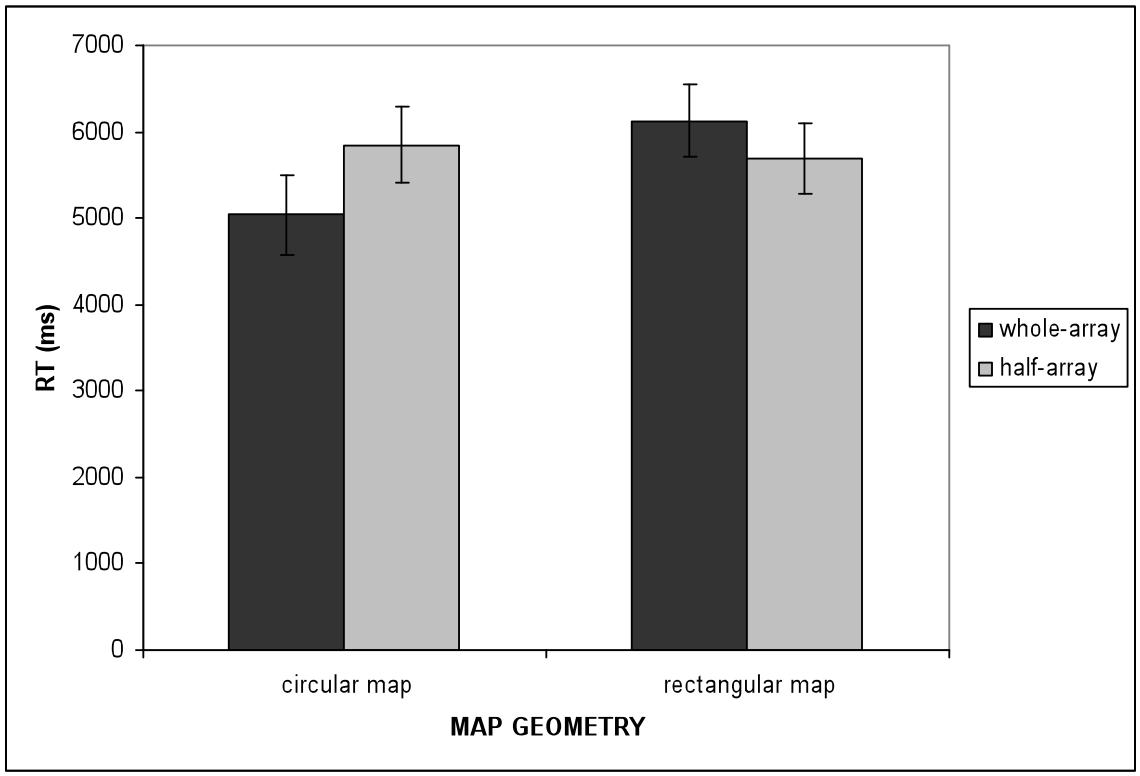


Figure 4-7 shows how framing geometry affects map and verbal preference accuracy.

Mental Representation did not show a main effect for either of the dependent measures. Accuracy data showed an interaction between Mental Representation X Array Accessibility, $F(1, 60) = 4.305$, $p < .05$, $MS_e = 17662992.17$. With circular maps, learning whole-arrays showed slightly faster responses and with rectangular maps, learning arrays in halves generated faster responses. Moreover, there was a reliable difference on performance after whole-array learning across geometry that learning circular maps in whole led to faster responses (see Figure 4-8).

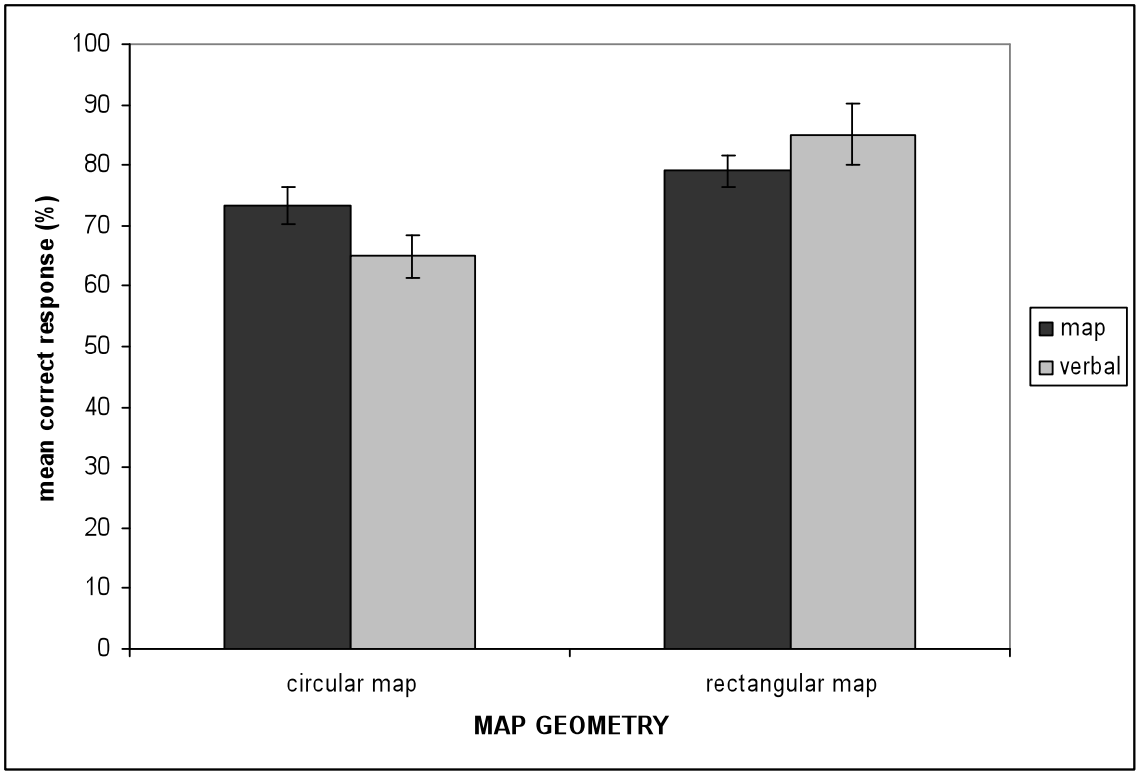


Figure 4-8. Mean rotation rates of whole- and half-arrays from memory as a function of map geometry.

Discussion

Experiment 4 used two tasks; view-array and map-array to test participants' performance after learning room-size spatial arrays from maps. Accessing learned layouts from memory suggested task-consistent viewpoint-dependency. When the task used map-like pictures with a bird's-eye view people showed better representation at learned viewpoints (0^0 and 180^0). Participants were faster accessing the layouts from memory for 0^0 and 180^0, two viewpoints they learned maps from, suggesting viewpoint-dependency (Shelton & McNamara, 1997; 2001; 2004). In contrast, with the view-array task, participants were faster and more accurate only at 0^0. In previous studies, participants learned room-size arrays with direct experience and recognized better from learned

viewpoints (Shelton & McNamara, 1997; 2001). We showed consistent results with map learning.

The amount of spatial information and how it is learned might affect strategies in accessing room-size arrays. Having a reference frame around environments resulted in better performance. In other words, spatial memory might be better for rectangular map where the frame provides additional spatial information. Yet, map geometry affected performance dependent on whether people learned the array as a whole- or half at a time. While whole-array learning seemed to be a better fit for circular map, half-array learning was better represented with rectangular map. Consistently, the performance pattern after whole- vs. half-array learning also showed the pattern indicative of strategy use, with responses getting faster for half-array learning with greater angular disparity for rectangular maps. Moreover, learning from circular map pulled whole- and half-array difference together as a function of angular disparity whereas rectangular map hindered "whole-array" performance and widened the difference between whole- and half-arrays. These results, together suggest how map geometry affected mental models. With no reference frame or environmental cue around the array, representations were forced to depict a more global representation, which are survey-like and engage in holistic strategy. With rectangular maps, there was the addition of a reference frame, and information from half of the array seems to be enough to access from memory and was better represented.

Preference was consistent with these findings. It affected performance on map geometry. People who preferred maps were more accurate with circular structure as opposed to verbal preference whereas preferring verbal descriptions showed more accuracy with rectangular maps. Consistent with the previous explanation, map

preference was hypothesized to use holistic strategy, which in turn is more efficient with global representations, namely "whole" arrays and circular maps.

Experiments 3 & 4: Interim Discussion

We examined memory of room-size arrays in relation to learned viewpoints as a function of room/map geometry and learning source (direct experience or map). As in the first two experiments, we suggested a mechanism for array learning, perspective taking, and cognitive strategies. People perform differently on spatial tasks and are suggested to apply different strategies; namely, holistic and piecemeal. While holistic processing requires mental manipulation of a figure as a whole, piecemeal approach engages piece-by-piece manipulation, which in turn might take longer. These strategies can also be observed in accessing room-size arrays from memory. Participants might perform differently with the information that is available to them (either whole array, or half array at a time). We proposed to observe similar patterns in performance among strategy-consistent learning, geometrical structure of the environment and learning source.

Learning layouts in whole or in halves suggested how accessible arrays were, in memory, and promoted the use of strategies. Whole-array learning was better represented with maps (Experiment 4). This is consistent with our predictions given that *whole* array learning was suggested to parallel with *holistic* strategy and *half* array learning would parallel *piecemeal* approach. We operationalized framing by learning with circular and rectangular geometries (Jansen-Osmann & Heil, 2007; Kelly et al., 2008; Mou et al., 2007). Rectangular geometry provided additional spatial information and a reference frame and people benefited from learning arrays within rectangular geometries as opposed to circular structure. More interesting finding was how *piecemeal* and *holistic*

strategy-consistent learning (whole-array vs. half-array) was selectively affected by room/map geometry. While rectangular room helped with the representation of half-array learning, whole-array learning led to better representation of the layouts learned within circular structures. Circular geometry seemed to provide a more global representation for layout memory that fit better with whole-array learning, which were holistic-strategy-consistent. Whereas rectangular geometry seemed to help a more local and piecemeal approach fitting better with half-array learning. Learning from rectangular structures (both rectangular room and rectangular map) slowed down the performance after whole-arrays. In other words, rectangular geometry hindered representation of arrays learned as a whole. This suggests that rotating the whole-array from memory was more demanding when there was an additional frame.

Learning the same layout from within the room or via map showed different representations as a function of angular disparity. Angular disparity effect shown with standard MR reaction (Shepard & Metzler, 1971) was observed for view-array task of direct experience (room condition). This might suggest possible similarities between manipulable size figure rotations and imagination of a layout from other viewing positions, a process known as perspective taking (Wraga et al., 2000). However, with map-array tasks for both direct experience and map learning, spatial memory showed more viewpoint-dependency (Mou et al., 2004; Roskos-Ewoldsen et al., 1998; Shelton & McNamara, 1997; 2001). Participants were faster with 0^0 and 180^0 degrees of rotation, slowing towards 90^0 (Easton & Sholl, 1995; Mou et al., 2009) from both directions creating a Λ-shaped response.

Since differences in MR rate, especially gender, pointed to differential strategy use (Heil & Jansen-Osmann, 2008; Kail et al., 1979; Maccoby & Jacklin, 1974; Naylor et al., unpublished data; Yuille & Steiger, 1982), the way people prefer to learn and represent spatial information might also reflect the use of *holistic* and *piecemeal* strategies. *Maps* provide *survey*-like representations and these representations are suggested to perform better with *holistic* processing. *Verbal* descriptions, however, provide sequential spatial information fitting better with more *landmark*-based and local representations, thus *piecemeal* strategy. As expected, we found that people who preferred maps and ones who relied more on survey perspectives were more accurate after learning within the room (Experiment 3). For map learning, preference affected map geometry. People who preferred maps better represented arrays depicted on circular maps, whereas ones preferring verbal descriptions showed better performance with rectangular structure (Experiment 4).

Solving mental rotation problems based on a learned array of objects in a navigable environment (Experiment 3) requires spatial perspective taking. Conversely, perspective taking, we suggested, engages mental rotation processes. Studies in the literature are divided such that while some argued perspective taking and mental rotation to be totally different from one another (Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001; Kozhevnikov et al., 2006) others suggested perspective taking to share common abilities between small- and larger-scale environments (Allen at al.,1996; Bell & Saucier, 2004; Boer, 1991). In examining performance on room-size arrays from memory and comparing this to standard MR tasks there are differences on perception, memory, and means of learning. We would discuss these limitations in General

Discussion. Spatial transformation of some sort, however, existed for both as was suggested in the literature (Allen et al., 1996; Hegarty et al., 2006; Hegarty & Waller, 2004, Kozhevnikov, Hegarty et al., 2001). The question was whether it is the same kind of transformation (Saucier et al., 2002)? Our results with framing and how it played into the visibility of strategies suggested that these two tasks drew on some kind of similar cognitive processes.

General Discussion

Going back to the couple Dave and Judy, who placed the sectional in their new living room, did Dave really mentally rotate faster? Did Dave and Judy use different strategies? If they did use different strategies, do individual differences (gender, spatial information preference, spatial representation) underlie their strategy choice? Furthermore, would any strategic differences hold when they navigated through parts of their city? Would strategic differences be evident if they learned the city either through direct experience or with maps? The present work examined cognitive processing similarities between mental rotation (MR) of manipulable objects and cognitive processes in memory of object arrays learned from either direct experience or maps. Further, it investigated how individual differences (gender, preference of spatial learning, or spatial representation tendencies) affect these kinds of mental manipulations. Taken together, we will examine whether performance on these tasks suggests strategy differences, such as holistic vs. piecemeal.

With a series of experiments, we showed the hallmark MR finding -- angular disparity effects on response time and accuracy. Experiments 1 and 2 supported MR

literature with increased RT and decreased accuracy rates as degrees of rotation between the object pairs increased (Shepard & Meztler, 1971). Memory of object-arrays showed effects of angular disparity with map tasks. As the magnitude of the discrepancy between the triad that included scenes from the room and learned layouts (from 0^0 and 180^0 viewpoints) increased, participants responded less rapidly and accurately. This finding suggests evidence of shared common processes between figure rotation and memory for the object arrays. Positive correlation between MR and perspective taking accuracy has also been found in the context of navigation in larger-scale environments (Hegarty et al., 2006; Kozhevnikov et al., 2006), but to our knowledge room-size arrays, which fall between manipulable single objects and navigating environments, have not been used with these studies. To further examine the extent of shared processes between MR and memory for object arrays, we focused on cognitive strategies people use during these tasks and the pattern that pinpoints these strategies. People who were faster and more accurate to rotate figures in their minds have been suggested to apply a more holistic approach whereas people who showed steeper slopes as a function of angular disparity relied more on a piecemeal strategy. We also introduced strategy-consistent stimuli to examine how people showing individual differences (ID) would handle whole and cut stimuli that were designed to elicit a particular strategy; holistic and piecemeal, respectively.

Factors such as gender (Kail et al., 1979; Linn & Petersen, 1985; Voyer et al., 1995), complexity (Bryden et al., 1990; Yuille & Steiger, 1982), and dimensionality (Bauer & Jolicoeur, 1996; Peters et al., 1995) appear to affect MR performance. Males performed better on 3-D figures than females (Peters et al., 1995) whereas performance

of females improved with 2-D rotation and the gender gap either was reduced (Heil & Jansen-Osmann, 2008; Peters et al., 1995) or not observed (Thomsen et al., 2000). Consistently, Experiment 1 found faster and more accurate male performance on 3-D MR while gender differences in 2-D MR were not reliable, even though the 2-D figures were relatively complex. Memory for room-size arrays, however, did not show gender differences, again consistent with the literature (Shelton & McNamara, 1997; 2001; 2004). Research has concluded spatial visualization and spatial rotation being two distinct abilities (Hegarty & Waller, 2004; Kaufmann, 2007; Kozhevnikov & Hegarty, 2001) finding difference between males and females for rotations but not with visualization tasks (Kaufmann, 2007). Response functions show similar patterns with angular disparity effect, and *strategy difference pattern* with strategy-consistent stimuli, individual differences, and frame. Thus, we suggest that tasks might require different abilities, which would not prevent them from sharing cognitive processes.

The underlying idea behind the present studies was that if gender reflects strategy differences, other individual factors (representation style and preference) should also reflect these strategies. Previous work has suggested that males use a more holistic strategy while females adopted a more piecemeal one (Jordan et al., 2002; Kail et al., 1979; Thomsen et al., 2000). As we expected, representation style and information preference showed differences in performance for both kinds of mental manipulation, i.e. mental rotation and perspective-taking. *Survey* representations led to better MR performance, consistent with the literature (Pazzaglia & DeBeni, 2001; 2006). Additionally, *survey-centered* people had more accurate array memory than *landmark-centered* individuals, both after learning from direct experience and from maps.

Experiment 3 also showed that individuals preferring *maps* more accurately imagined learned arrays from other viewpoints. These data hinted to possible differences in room-size array learning and with the following results they indicated possible strategy differences.

We observed *strategy difference pattern* for other factors. As the amount of required rotation increased, performance difference between strategy-consistent stimuli (whole vs. cut/half), and strategy users (males vs. females, people who preferred map vs. verbal descriptions, and survey- vs. landmark-centered people) became more evident. We manipulated cut stimuli to elicit piecemeal processing, and it seemed to be successful. Females, people with verbal description preference, and landmark representations showed similar patterns as cut stimuli, suggesting that they too might have used piecemeal strategy. In other words, all of these variables (complexity, gender, preference, and representation style) showed the result pattern that has been hypothesized to reflect holistic and piecemeal strategies, which is an interesting and new finding for the literature.

One other factor we introduced to examine how people process mental manipulations was framing the stimuli. Having a frame adds reference points around the object or an array of objects. We framed 3-D and 2-D MR stimuli for the first two experiments. To operationalize framing we created circular (unframed) and rectangular (framed) structures around the arrays for the last two experiments. We expected to find better performance with framing, especially by piecemeal strategists. Since piecemeal approach processes spatial information in pieces, having an extra cue might help their processing rate. Consistently with the literature (Kelly et al., 2008; Kelly & McNamara,

2008; Mou et al., 2009; Mou et al., 2007; Wang & Spelke, 2000), we found that the geometry of the surrounding affected array representation. Learning arrays within a rectangular room or from a rectangular map benefited the resultant performance with better accuracy.

Frame interacted with strategy-consistent stimuli (whole vs. cut/half). While participants were more accurate learning in rectangular room from both direct experience and maps, they were slower after whole array learning with rectangular structures. For most of the experiments (2, 3, and 4) framing hindered performance on "whole" figure/array yet when figures were 3-D, "whole" figures benefited and "cut' figure rotation was affected negatively. The discrepancy across experiments cannot only be dimensionality, because navigating within a room also provided 3-D learning. We suggest, as earlier, that frame reduced the perceived depth of the 3-D figures by providing a flatness cue (Eby & Braunstein, 1995; Reinhardt-Rutland, 2003). Inconsistent dimensionality among the figure (target) and the background (frame) in Experiment 1 possibly confused participants and slowed down the rotation of cut figures. People might have been affected more negatively while rotating cut figures, which were used to elicit piecemeal processing, because of this clash in dimensionality and frame. However, holistic strategists were not expected to perform differently with or without a frame because they were suggested to represent the figure more globally without relying on any additional cue. Moreover, room learning (Experiment 3) was not affected by this perceived flatness because while learning the array there was no clash of perceived dimensionality, and they completed the tasks basing on the representation of the array in

their memory. Together these findings further support the existence of similar cognitive strategies for rotational processes for figures and memory of object-arrays.

Researchers found spatial memory and representations to be viewpoint-dependent (Diwadkar & McNamara, 1997; Mou et al., 2004; Mou & McNamara, 2002; Roskos-Ewoldsen, McNamara, Shelton, & Carr, 1998; Shelton & McNamara, 1997; 2004). In the literature, viewpoint-dependency has been shown with direct experience of room-size arrays. However, in our research both direct experience and map learning hinted at viewpoint-dependency, suggesting a more interesting finding. Circular room, which enabled the formation of a more survey-like representation, hinted viewpoint-dependency with whole-arrays whereas rectangular room showed viewpoint-dependency with half-array learning. We suggest that learning source selectively shows viewpoint-dependency in situations where it matches the strategy with which spatial information is processed. Moreover, rectangular map learning negatively affected "whole-array" performance. Frame, for both room and map conditions, seemed to benefit accessing half-array from memory more. Consistent with our predictions, rectangular geometry added a new reference frame and environmental cue to process spatial information. However, with this additional information and limited capacity to access objects from memory, learning half array at a time was enough of a cognitive load. To sum up, participants seemed to selectively favor processing of whole vs. half array, consistent with the strategy they use, with room-size arrays (learned from rectangular- or circular geometries).

Learning source showed differences in task performance of room-size arrays from memory. It might be explained with the way information was acquired. Perspective we use during learning affects spatial processing (Bilge & Taylor, 2009; Brunyé & Taylor,

2008; Sholl, 1987; Taylor & Tversky, 1996; Thorndyke & Hayes-Roth, 1982). Direct experience and maps led to different results especially after whole- and half-array learning and geometry. While whole-array learning showed more accuracy with maps, direct experience did not find this effect. Moreover, map learning showed preference interacting with geometrical structure around the layout. People who preferred maps in learning spatial information were more accurate with circular maps, and ones who preferred verbal directions better represented the array with rectangular maps. This might be the case, because circular map use in unconventional and it forces even a more global representation style with map learning. This is not the case with direct experience, so can explain why this was not observed with Experiment 3. Active movement within the environment was found to improve spatial performance (Wang & Simons, 1999), and that might be why framing effects were not observed with direct experience. This leads us to explanation of a mechanism underlying cognitive style and stratgey differences and limitations of the current research.

We use an explanation to propose a mechanism for the result patterns of different variables and how they reflect strategies used in MR, then conclude that there are more similarities and shared processes between MR and memory of room-size arrays than differences (see Figure 5 for a review). In everyday life, we move within environments, gather spatial information through different sources and create spatial mental models. With *direct experience* of the environment people engage in psychomotor processes where they see, stand, move, or walk in the environments. As they walk, they can observe information within their eye range. Direct experience also uses *landmark* or *route* perspective which helps create mental models with incoming *sequential* information.

This is similar to *piecemeal* strategy in MR. Whereas with secondary means of spatial learning such as maps *survey* perspective with a bird's-eye-view is used (Pazzaglia & De Beni, 2001; Taylor & Tversky, 1996). While landmark or route perspective is based on a more *egocentric* (self-to-obejct) representation, *survey* perspective is a more *global* and *allocentric* (object-to-obejct) representation, similar to *holistic* view and strategy of MR. Learning source differences might account for inconsistent results between direct experience (Experiment 3) and map learning (Experiment 4).

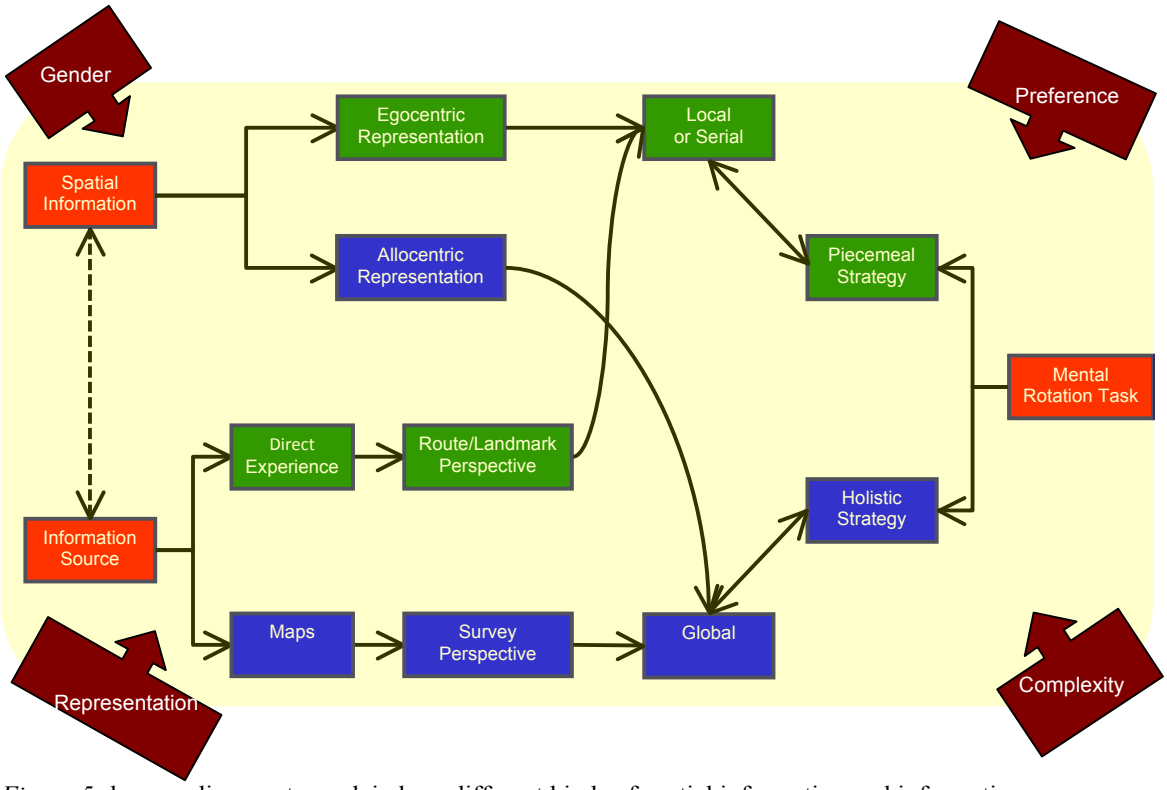


Figure 5 shows a diagram to explain how different kinds of spatial information and information source are represented in the mind with the effects from individual factors and complexity.

Differences between stimuli and the tasks of MR and room-size arrays characterize the shortcomings of the study. First, with MR there is a single, manipulable object at each trial whereas with room-size environments there instead is an array of objects. Mental rotation task either had 3-D figures with 10 cubes or 2-D abstract and complex figures. Even though they differ in that sense, each array had 9 objects as we

tried to match the difficulty level. Second, in MR object positions are moved while one's position in the environment does not. The opposite is true with perspective taking wherein the relations between the objects are stable and one's own position changes (Hegarty & Waller, 2004; Rieser, 1989). Self-rotation, even imaginary, yielded more accurate and faster performance than imaginary rotation of the object array (Wraga et al., 2000). Future studies might examine how these two tasks can be made more compatible. Participants could be stationary while arrays moved to different orientations by the experimenter. Third, larger-scale environments have a potential for different means of learning (direct experience vs. map) whereas small-scale standard MR figures can only be experienced with one type of learning. We tried to control for it by matching the tasks in Experiments 3 and 4 (view-array and map-array tasks) with 3- and 2-D properties of the stimuli. Fourth limitation lies in memory and how long they store spatial information for. While Experiments 3 and 4 relied on spatial memory, Experiments 1 and 2 relied on online spatial processing. Participants solved typical MR problems by deciding whether the presented pair was the same or mirror reflection of the other as the pair is presented on the screen. However, with room-size arrays, they access an array of objects from previous learning, thus from memory. With spatial memory, egocentric and allocentric representations (Easton & Sholl, 1995; Sholl, 1995), viewpoint-dependent spatial mental models (Levine et al., 1982; Shelton & McNamara, 1997; 2001; 2004; Mou & McNamara, 2002) or mental models relying on intrinsic reference frames (Mou et al., 2007; Mou, Fan, McNamara, & Owen, 2008a; Mou, Xiao, & McNamara, 2008b; Mou & McNamara, 2002; Mou, Liu, & McNamara, 2009) need to be taken into account. Future studies can address this issue by asking array questions while the person is in the room or

directly experiencing smaller mental rotation figures. Haptic learning of wooden replicas (Robert & Chevrier, 2003) might eliminate these problems.

The use of desktop virtual environments has become prevalent. Since virtual reality allows for stricter control among learning conditions, and similarities across real and virtual settings have been shown (Hegarty et al., 2006; Montello, Waller, Hegarty, & Richardson, 2004) future studies can use virtual reality instead of direct experience with room-size arrays. Another method to further investigate strategies in mental rotation is eye-tracking. Getting data from eye-movements when presented with a form of mental rotation task might explain where people are scanning first and how they proceed. Basing on our research and predictions, the difference between holistic and piecemeal strategies would be more easily observed and reported with greater confidence since different strategies would solve the problem through different scanning techniques. In addition, experience with larger-scale environments could also be investigated along with MR task.

Implications

Current research has its implications in everyday life. Starting with spatial information processing in our daily lives we interact with maps, or we walk through new places trying to create mental maps for these environment. It is possible that one of the routes we generally take might be closed one day, and we would need to come up with a different route trying to imagine being at another point while rotating the learned representation in our heads. If mental rotation ability is similar for manipulable objects and larger environments, then tests specifically and thoroughly examining cognitive strategies in mental rotation could predict mental manipulation of environments.

Global positioning system (GPS) devices are more relied upon and number of people who use GPS is on the rise (GPS Goes Mainsteam, 2007). Even smart phones frequently have GPS systems nowadays. All these factors encourage the research on how perspectives and learning modality affect spatial representations and how mental rotation might be processed with these representations.

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Appendix A

Participant #___

QUESTIONNAIRE

Please indicate your answer to each of the following statements by placing a circle around the appropriate number (1, 2, 3, 4, or 5).

1. Do you think you have a good sense of direction?

1	2	3	4	5
Not at all				*Very Good*

2. Are you considered, by your family or friends, to have a good sense of direction?

1	2	3	4	5
Not at all				*Very Much*

3. Think about the way you orient yourself in different environments around you. Would you describe yourself as a person:

   a. Who orients him/herself by remembering routes connecting one place to another?

1	2	3	4	5
Not at all				*Very Much*

   b. Who orients him/herself by looking for well-known landmarks?

1	2	3	4	5
Not at all				*Very Much*

   c. Who tries to create a map of the environment in your head?

1	2	3	4	5
Not at all				*Very Much*

4. Think of an unfamiliar city. Write the name of that city here: _____
   Now, try to classify your representation of that city:

   a. Is your memory map-like (like a birds-eye view of the city):

1	2	3	4	5
Not at all				*Very Much*

   b. Is your memory route-based (like a first-person view of the city):

1	2	3	4	5
Not at all				*Very Much*

   c. Is your memory landmark-centered; that is, memorization of single salient landmarks, such as monuments, buildings, or crossroads:

1	2	3	4	5
Not at all				*Very Much*

5. When you are in a natural open environment (mountains, seaside, countryside), do you naturally know cardinal points? That is, do you know where North, South, East, and West are?

1 2 3 4 5
Not at all *Very Much*

6. When you are in your home-town or city, do you naturally know cardinal points? That is, do you know where North, South, East, and West are?

1 2 3 4 5
Not at all *Very Much*

7. If someone is describing the route for you to reach, do you prefer:
   a. To make a mental image of the route (imagine it)?

1 2 3 4 5
Not at all *Very Much*

   b. To remember the description verbally (remember the distances, landmarks, and turns)?

1 2 3 4 5
Not at all *Very Much*

8. In a complex building (store, museum) do you think spontaneously and easily about your direction in relation to the general structure of the building and the external environment?

1 2 3 4 5
Not at all *Very Much*

9. When you are inside a building can you easily visualize what there is outside of the building in the direction you are looking?

1 2 3 4 5
Not at all *Very Much*

10. When you are in an open space and you are required to indicate a compass direction (North, South, East, West), do you:
    a. Point immediately?
    b. Need to think before pointing?
    c. Have difficulty?

11. When you are in a complex building (with many floors, stairs, corridors) and you have to indicate where the entrance is, do you:
    a. Point immediately?
    b. Need to think before pointing?
    c. Have difficulty?